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Optimization of the operation of a Microgrid with renewable energy resources

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Abstract

Nowadays, due to the growing overpopulation on earth, resources are running out and the demand for these is increasing. Non-renewable energy, such as fossil fuels or nuclear energy, will eventually run out, making it a foreseeable necessity to find new and green ways of producing energy. It is also reasonable to assume, that renewable energy will eventually render a greater share of the worldwide energy mix. The increasing importance of Microgrids and consequently the motivation of this project is due to the improvement in efficiency, reliability, security, quality and sustainability.

This Bachelor's Thesis will focus on the powering of an autonomous (disconnected from the Main Grid) Microgrid system through the main use of these renewable technologies. The operation objective is to minimize operating costs by maximizing the renewable energy usage. The Microgrid will power 62 houses of different characteristics, all of them with solar panels and 9 of them with wind turbines. Following the procedure of document [1], a centralized battery system is used. In order to secure the fully autonomous mode and the electrical security in our grid, the inclusion of auxiliary generators was studied.

First, the components of the grid will be dimensioned to have an overall idea of the limits of the optimization problem, and then a simulation at different time points of the year (average case, most disadvantageous case and most favorable case) will be done with existing electrical consumption data of different types of households. After that, the optimal operation of our resources will be studied with MATLAB focusing on the cost of operation and rewarding the use of renewable sources. This study results in the following final sizing, taking as optimal the most disadvantageous case: **691** solar panels, **9** wind turbines, **35** batteries and **6** auxiliary generators (5 big ones and one smaller one), with a total nominal power of **3,2 MWh.**

The studied system renders energetically feasible but not economically given an electricity price of 60€/MWh, this is due to several reasons; being: the assumptions used to model the system don't take into account subsidies and tariffs, different pricing for different periods of the day/year, current renewable technology having too large fixed and capital costs, etc. Also, it is due to the perpetuity model used to model the future revenue streams, where it has been assumed that consumption stays constant along with price.

To sum up, this project has been motivated by the increased future importance of autonomous Microgrids and their feasibility both energetically and economically, the first one has been

proven, it is possible to supply a whole autonomous Microgrid with renewable energy however under these assumptions and current technology it isn't possible to do so in a profitable fashion.

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Definitions, acronyms and abbreviations

C= Charging rate

CCI=Consumer Confidence Index

CPI= Consumer Price Indx

DER= Distributed energy resource

DG= Distributed Generation

DoD= Depth of Discharge

EU= European Union

GDP= Gross Domestic Product

HAWT= Horizontal axis wind turbine

LCOE= Levelized Cost of Electricity

LCOS= Levelized Cost of Storage

LP = Linear programming

LV= Low Voltage

MV= Medium Voltage

MG = Microgrid

MCP = Mixed complementarity programming

MILP = Mixed-integer linear programming

MINLP = Mixed-integer nonlinear programming

NLP = Nonlinear programming

PV= Photovoltaic

Rpm= Revolutions per minute

QP = Quadratic programming

US= United States of America

VAT= Value-added tax

VAWT= Vertical axis wind turbine

NPV= Net present value

WT= Wind turbine

Preface

Origin and motivation of the project

Renewable energies such as solar and wind energy are exponentially increasing in the last years. The prediction for 2040, is that total global generation capacity will grow by more than 60% and 45% of this generation will come from renewable resources. More and more people are becoming aware of the exhaustion of non-renewable sources and the need to invest in new forms of generation. Governments and institutions are setting objectives to force the world into a change, however small it may be. For example, in Europe, the program of the Horizon 2020 from the European commission has set objectives that member states must respect and work towards to achieve them. It is structured around seven specific objectives and research areas [2]:

- Reducing energy consumption and carbon footprint
- Low-cost, low-carbon electricity supply
- Alternative fuels and mobile energy sources
- A single, smart European electricity grid
- New knowledge and technologies
- Robust decision making and public engagement
- Market uptake of energy and ICT innovation

Hybrid power plants are a solution to cover up more energy demand. The use of different sources of energy, like solar and wind energy, and a battery storage system, results in a system that it is not only more sustainable but also more affordable and reliable. Depending of numerous factors, especially meteorological conditions, different combinations can be made to ensure the generation's continuity.

Introduction

Objectives of the project

The objective of this project is to create a code to minimize the costs of a renewable hybrid power Microgrid. This can then be transferred to any type of problem in which the installation of a Microgrid with solar and wind generation anywhere in the world is sought to be optimized.

To achieve this goal, a few preliminary steps will be necessary. First of all, the dimensioning of the generation and storage system. In order to do this, the following information is essential:

- The meteorological data of the area in which the Microgrid is to be installed
- The specifications of each type of user in order to adapt the solutions
- The objective of the project must be clear (rewarding the use of renewables, just looking at the cost, etc.)

Then, developing a code to optimize the costs whilst assuring the continuity of the electrical source and the security of the grid.

Finally, make an assessment to determine whether the project is suitable and feasible.

Scope of the project

In order to achieve the objective of the study, several tasks have been carried out throughout the course of the project:

- Research on how hybrid power system works and the components of the grid
- Research on MG in islanded mode
- Research on the best technologies taking into account the needs of the specific grid
- Dimensioning of several items of the grid:
    - Solar arrays
    - Wind turbines
    - Capacity of the battery
- Considerations of the MG to simplify the coding
- Research on optimization using MATLAB
- Code the optimization problem in MATLAB
- Study the outcome of the optimization problem in environmental and economic point of view

1 State of the art

1.1 Renewable energies

Energy consumption steadily rising, along with an increased conscience of our print on the planet has shifted the mix of energies which provide our basic needs. Some of the drivers of such an increased trend are the improvement in the living quality standards, secondly the increased penetration and functionality of electronic devices, i.e. phones and computers, which are now available to wider range of consumers and thirdly the increase in globalization which has resulted in an increased worldwide transport of goods and people.

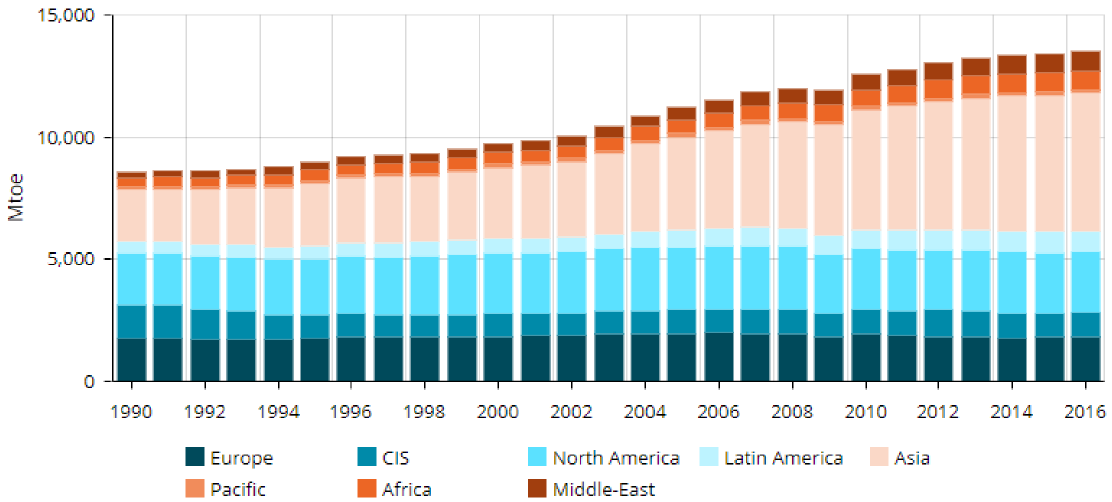

Figure 1: Energy consumption [3]

Nowadays, the renewable energy market is constantly increasing and a greater hare belongs to renewable sources. As you can see in the following figure, 24% of the electricity production worldwide comes from a renewable source.

Figure 2: Percentage of production of renewable/non-renewable [3]

The most common sources of renewable energy are solar (2%) and wind (5%) as shown in the right figure below. The share of wind and solar energies have seen a steady and exponential growth as shown in the left figure below.

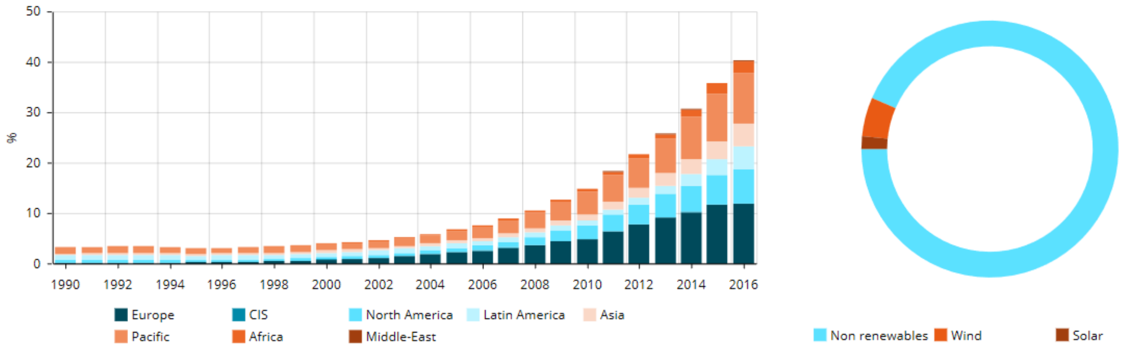

Figure 3: Share of wind and solar in electricity production worldwide [3]

Focusing on Spain, where our area of study is located, these percentages are much higher, 6% for solar energy and 22% for wind generation. Even thought, in the last 4 years the growth has been reduced and stayed constant, as shown in left picture bellow.

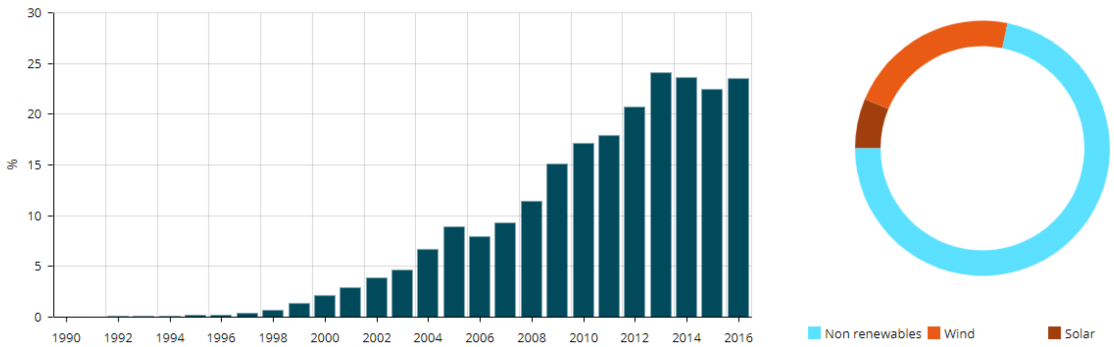

Figure 4: Share of wind and solar in electricity production in Spain [3]

The historic evolution of electric generation from 1960 to around 2014 is shown in the following figure. First of all, it is noticeable that hydroelectric generation is the first renewable source of energy with a generation between 1960 and 1970 highly superior to carbon generation. Then nuclear generation begun and grew very fast. The second and third renewable source of energy were thermic and wind generation. Even though, thermic source is almost negligible in comparison to all other sources. The latest renewable source to grew in Spain was solar generation, but as this new technology is very recent compared to other energy fonts, a steady increase is expected in the future.

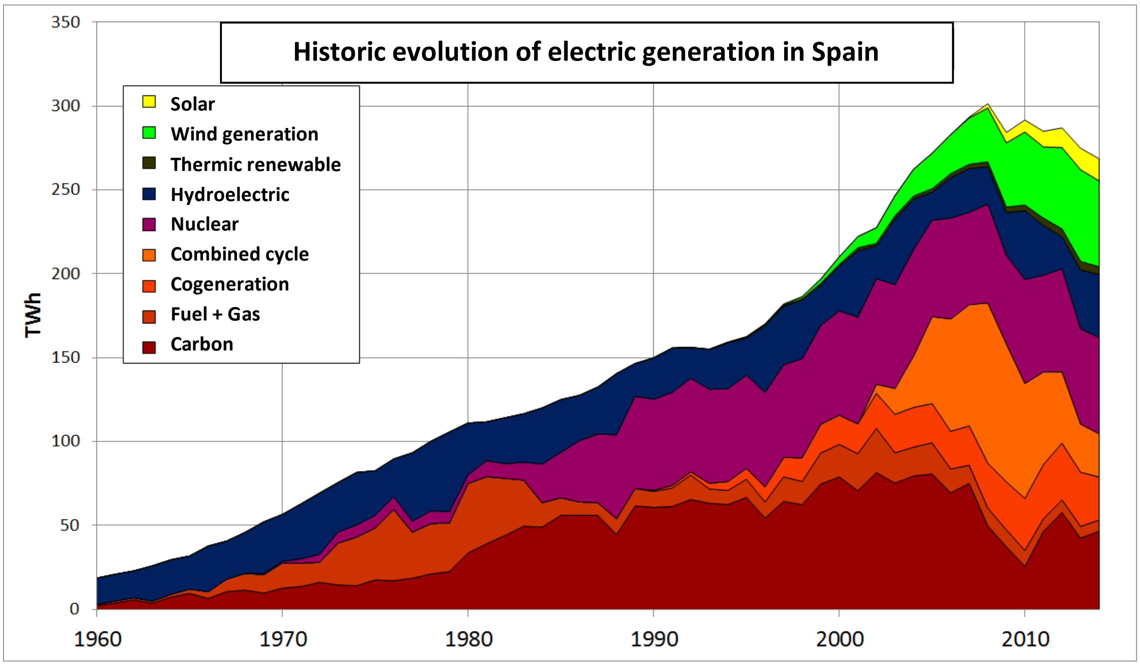

Figure 5: Historic evolution of electric generation in Spain [4]

Microgeneration of renewable energy refers to small-scale electricity generation from the wind or sun. [5]

The essential sources of renewable energy are as follows, [6]:

- <u>Wind Power</u>

  The first wind turbine used to generate electricity was built in 1891. Currently, this is one of the fastest-growing energy sources; the wind capacity has nearly doubled from 2012 until 2017 and has now 539,581 MW of installed capacity. The potential of wind power is huge and it is the least expensive renewable source available; the levelized cost of energy is around 35€/MWh, a third of the LCOE of solar panels. Large wind turbines cannot be installed in close proximity, but given that they have a relatively small base, the area around them can be used for other purposes, which makes them very useful for agricultural purposes and a very suitable solution for domestic use.

The biggest disadvantage with wind energy is, it is becoming increasingly unpredictable and unsteady due to climate change reasons. Therefore, making it difficult to rely on this energy source alone, not at least until efficient enough and low price batteries are produced. [7]

- Solar Power

Photovoltaic panels, solar collectors and thin-film solar sheeting capture sunlight and turn it into electricity, with an average cost of 100€/MWh. There are many advantages of the production and use of solar energy being its great potential; the earth's surface receives 120,000 terawatts of solar radiation, which means that one year of solar energy reaching the Earth would be twice the amount of non-renewable resources. Even though there are emissions associated with its manufacturing, the balance for the environment is overall very positive and it has a widespread range of uses, from domestic to space investigation.

As every other technology, it also comes with some disadvantages. Sunlight is an intermittent energy source, as it is only available during daytime and even during the day, the source is unpredictable and depends on other weather conditions. Given its intermittency, the use of energy storage is basic, which is yet very expensive. It is also a very land intensive making this energy's return on investment improvable. [8]

- Biomass

Biomass power is carbon neutral electricity generated from renewable organic waste. [9] The advantages of this source of energy is that not only you generate electricity with a low environmental impact and low costs (around 55€/MWh), but it also helps with waste management.

There are also some disadvantages. As you need to burn the waste to produce biomass, it is a source of pollution, so even if it comes from a renewable source it is not entirely good for the environment. It is also expensive and not very efficient. [10]

- Geothermal Energy

Geothermal energy is the use of heated water and steam from the Earth to run power stations, which turn steam into electricity. Geothermal reservoirs come from natural resources and are naturally replenished with a massive potential. Contrary to the solar and wind power, geothermal power is a stable source; the power output can be predicted with a remarkable accuracy.

The disadvantages of this source of energy are the following. There are greenhouse gases below the surface of the Earth, the emission of these gases tend to be higher near the power plants. When constructing a geothermal power plant, the stability of land can be affected and lead to earthquakes. It is an expensive source of energy, specially the exploration and drilling of new reservoirs. Then the running of the plant is not very expensive (around 100€/MWh).

- Hydroelectric power

Hydroelectric plants use running water, such as rivers or ocean tides, to power turbines. Around 17% of world electricity consumption in 2014 was generated with hydroelectricity [11]. It is a very reliable, flexible (because adjusting water flow and output electricity is easy) and safe source of energy.

The disadvantages of this source of energy are the following. To construct a hydroelectric power plant, you need to change nature, altering water flows or damming of water currents, which can affect the wildlife, especially fish and micro-wildlife. The initial installations costs of a hydroelectric plant are rather high, but overall it is not an expensive source of energy, 80€/MWh. It is a more stable and predictable source than solar and wind, but has a high risk from droughts, a problem that is increasing due to climate change.

1.1.1 Solar power

In this chapter, a study of how solar panels work to produce power will be done relying on the following source: [12].

Firstly, in the following figure the solar energy system market layout is shown. Off -grid system for consumers will be the focus of this project, which is only a small fraction of the solar technologies market.

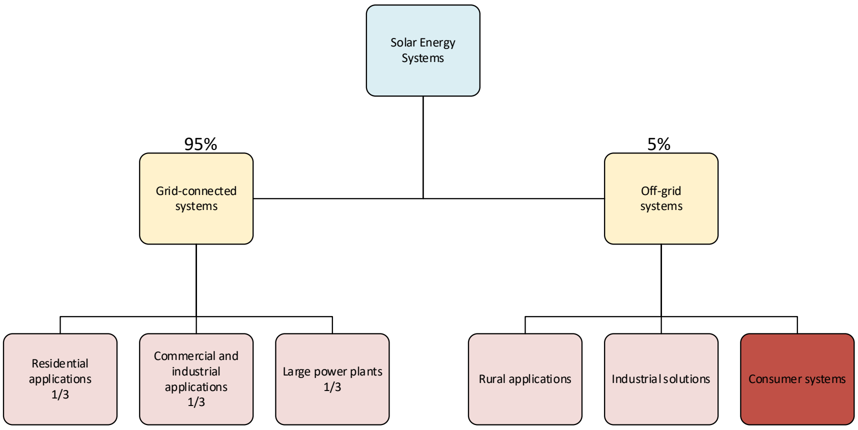

Figure 6: Photovoltaic market segments (Own elaboration)

A solar cell is an electronic device, consistent of several layers of semiconductor materials with different electric and electronic properties; it converts sunlight into electric energy (DC, direct current). A photodiode, a diode which, when exposed to light, generates a potential difference or varies its electrical resistance, and, in the absence of light, behaves like a normal diode. A solar cell behaves like a large area of photodiodes, but with the difference that solar cells are optimized to have the maximum conversion efficiency of the incident light into electrical energy and photodiodes maximize the photocurrent and minimize the dark current.

As schematized in the following figure, there are two layers of silicon wafer, one is n-type material and the other is p-type material, it makes a p-n junction. The incidents photons of the sunlight are absorbed by the Metal Grid (Front contact), and pairs of holes and electrons are generated in both regions of the union. In this p-n junction, there is hole diffusion from p to n region and free electrons from n to p region. The displacement of charge leaves a positive or negative electric charge in the p region and the n region respectively, which creates an electric field E from n to p region, building up the electrical voltage.

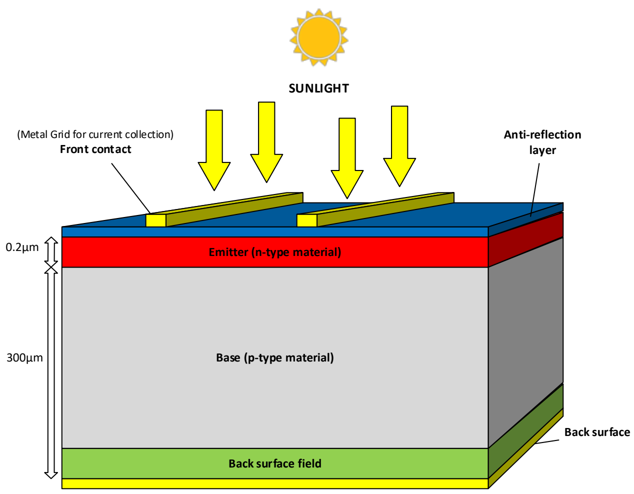

Figure 7: Schematic drawing of a silicone solar cell (Own elaboration)

As this technology uses solar radiation as its primary source, following are brief definitions of the different types of radiation:

- **Direct**: This is the solar radiation traveling on a straight line; it is the biggest and most important component in solar panels representing an 85% of the total insolation [W/m^2].
- **Diffuse**: Describes the sunlight that has been scattered by molecules and particles in the atmosphere but that has still made it down to the surface of the earth. It is very small compared to direct irradiation, it only represents 15% of the total insolation [W/m^2].
- **Global**: The addition of direct and diffuse irradiation [W/m^2].
- **Reflected**: Also called Albedo, it is the direct and diffuse radiation received by the reflection on a surface (the ground or other surfaces). The percentage of reflection varies depending on the material; it goes from 4% with asphalt to 80-90% with fresh snow [W/m^2]

Solar panels power output is largely dependent on the solar cell technology, the following table presents a comparison between available cell technologies, it can be seen that even though the Monocrystalline Module has a greater payback period, its efficiency and service life are also quite higher than the other two competitors.

	Monocrystalline Silicon Modules	**Polycrystalline silicone modules**	**Thin-Film solar cells (TFSC)**
Energy pay-back	2,5 years	1,5 years	1 year
Efficiency	16% - 21%	13% - 18%	12% - 18%
Space	+	++	+++
Service life	30-40 years (25-year warranty)	+ 25 years	20 years
Price	++	+	+

Table 1: Comparison between available cell technologies

1.1.2 Wind power

This chapter will study wind turbine principles and operation [13].

Wind turbine blades have a particular shape and geometry that causes, when air flows on both blade sides, a differential in pressure between blade-sides. This differential in pressure exerts a force that drives the blade to move around the axis. On the top of the turbine, a weather vane, connected to a computer and other weather vanes, keeps the turbine at the precise angle for optimum operation given a preset level of production. The speed at which blades usually turnaround is that of 18rpm (for bigger WT), which per se, isn't enough to produce quantifiable energy. Hence, the rotor has a gear box inside which increases this speed to 1800 rpm (x100), a speed which now is enough to produce electricity.

Wind turbine size has a huge impact in the output. These are the most common types of wind turbines:

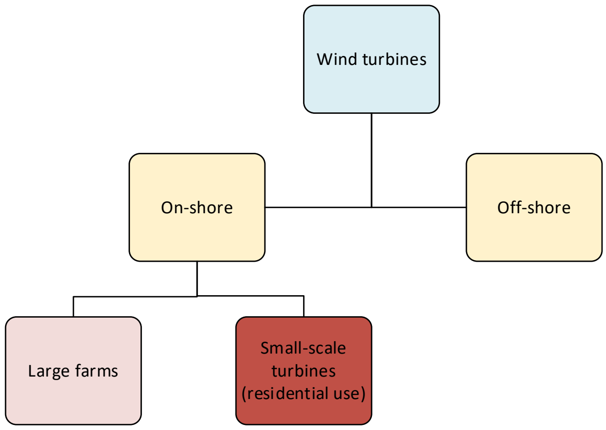

Figure 8: Different types of wind generation

Wind turbines can be built on-shore or off-shore. On-shore means that the wind turbine is built on the ground and off-shore means that the wind turbines are installed on oceans or lakes generally in either shallow waters or a floating format.

The project will focus on small-scale turbines, power generation systems with the capacity to produce up to 50kW of electrical power (therefore, for residential use, it is around 1-3kW).

There are also different types of wind turbines:

- Horizontal axis wind turbines (HAWT) ((a) and (b) in the following figure), thiese are the most commonly used. They typically have either two or three blades.
- Vertical axis wind turbines (VAWT) ((c) in the following figure), that has had very small commercial success. Therefore, its main advantage is that they do not need any kind of weather control, and the respective computer, to keep them facing the wind.

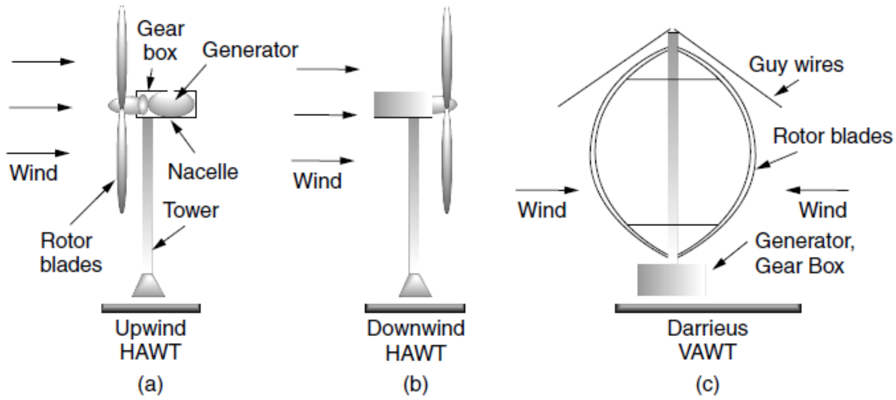

Figure 9: Horizontal and vertical axis turbines [14]

1.2 Energy storage

1.2.1 Batteries

How does a battery work?

A battery is simply an element which is able to store and convert chemical energy into electrical energy. In addition, two basic types must be distinguished: **primary batteries** that are single-use, as in the case of life-long non-rechargeable batteries, and **secondary batteries**, which are rechargeable because their electrochemical reactions are reversible which will be the focus of this project. The batteries composition, at a very basic level, are made up of three elements that can be of very diverse materials, an anode, a cathode and electrolyte. [15]

				Lithium Ion	
	Lead acid	Nickel Cadmium	Nickel Metal Hydride	Graphite/NMC	Titanate Oxide
Energy Density	40 Wh/kg	45-60 Wh/kg	80 Wh/kg	120-200 Wh/kg	70-80 Wh/kg
Cycles	200-300	1000-1500	300-500	500-3000	15000-20000
Charge power	★	★★★	★★★	★★★	★★★★★
Discharge power	★★★★★	★★★★★	★★★★★	★★★★★	★★★★★
Energy efficiency	★	★★★	★★★	★★★★★	★★★★★
Nominal cell voltage	2.0 V	1.2 V	1.2 V	3.6 V	2.3 V

Table 2: Comparison table of different types of batteries [16]

As shown in the table above, there are several types of batteries. The most common technologies are lead acid and Lithium Ion [17].

- Lead acid

These batteries date from the 19th century and are the most common batteries. The advantages of these batteries are that they are the less expensive and have a high number of uses. However, as exposed in the table above, the capacity is not very high, it is not very efficient and has short lifetime. In addition, the depth of discharge is relatively poor and low ability to operate in a partially loaded state.

How does these batteries work?

The battery uses a reversible chemical reaction, using lead plates and an electrolyte, to store energy [18].

- Lithium Ion

These batteries are increasingly replacing lead acid batteries. As the table above shows, they have a longer life, high energy density and higher efficiency. The most important disadvantage of these batteries is that it requires advanced manufacturing capabilities to achieve high yields.

How does these batteries work?

The battery is built of a metallic case and three sheets, a positive electrode ($LiCoO_2$), a negative electrode (made of carbon) and a separator between the other two. This three are submerged in an electrolyte solution. The lithium (Li) ions goes from the positive electrode to the negative when charging the battery and from the negative to the positive when discharging. [19]

1.3 <u>Microgrid</u>

The definition of a Microgrid (MG) is a small network of electricity users with a local source of supply that is usually attached to a centralized national grid but is able to function independently.

The U.S. Department of Energy Microgrid Exchange Group defines it as *"a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A Microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode."* [20]

Or by the CIGRÉ C6.22 Working Group, Microgrid Evolution Roadmap as "*electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while is landed*."

The Microgrid institute defines it as "*A small energy system capable of balancing captive supply and demand resources to maintain stable service within a defined boundary. There is no universally accepted minimum or maximum size for a Microgrid*." [21]

Microgrids combine various distributed energy resources (DER), which is any form of decentralized generation, storage or demand management capability [21].

MG can be sorted by five categories [21]:

- **Off-grid Microgrids**: MG systems not connected to the local utility network, such as islands, remote sites…
- **Campus Microgrids**: MG systems fully connect to the local utility network. However, this type of MG can also maintain some level of service in off-grid mode for example during a utility outage.
- **Community Microgrids**: Integrated into the utility network, these Microgrids supply consumers and services within a community.
- **District Energy Microgrids:** These MG provide electricity and thermal energy.
- **Nanogrids:** The network is made up of the smallest discrete network drives with the ability to operate independently. It can be a single household or a single energy domain.

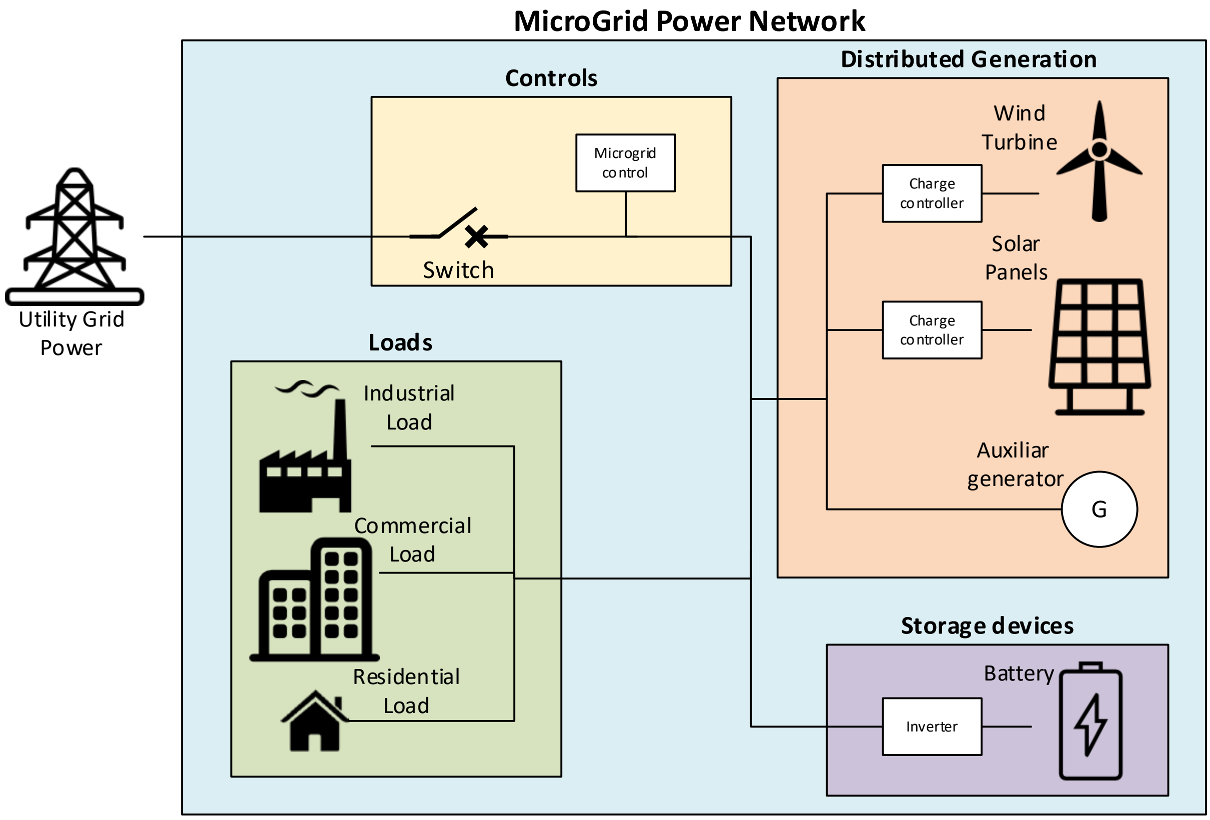

Figure 10: Microgrid (Own elaboration)

The figure above schematizes the Microgrid, which is composed mainly of the following components:

- **Distributed generation (DG),** [21]**,** [22]**,** [14]

Distributed generation is the term used to describe small-scale power generation located on the distribution system near an end-user customer. For example, a house can produce its own electricity with solar panels or small wind turbines or in a bigger scale, a whole island could produce its own electricity with a combination of sources of energy such as hydropower plants, solar panels, and wind turbines. This kind of generation has the following attributes:

- Decentralised
- Not controlled by the main network
- Typically, less than 50MW

There are plenty of advantages with this system. First, the losses due to the long distances that energy travels (around 9,5%) are greatly reduced when transported from a centralized. The grids are sensible to destruction during natural disasters such as earthquakes, hurricanes… with DG, the risk of losing electricity access decreases. When deciding to have own sources of generating electricity, people tend to choose renewable energies because of lower costs, greater future and responsibility with the environment so it is also a measure to reduce the environmental impact.

There are also disadvantages when using this system. Generally, renewable energy sources are intermittent sources (as explained in previous chapter 1.1) such as wind a solar generation, to assure the continuous access to electricity, the installation of storage systems (batteries) and backup systems (auxiliary generators) is essential, which results in a considerable cost increase, especially due to the storage systems. [23]

- **Controls** [24]**,** [25]

The switch allows the Microgrid to operate in isolated or connected mode to the central grid. With the introduction of DER, the grid is now an active system with distributed control and bidirectional power flow. The MG has to be able to connect or disconnect (if it is the case) from the general grid, as well as balance and control the voltage in the grid and the power flows. The system responsible of the controls is the Energy Management System (EMS); it selects the power of each element of the grid, solar generation, wind generation, auxiliary generators and batteries in this project.

- **Loads** [20]

From industrial loads to a single house, loads of a Microgrid can be very different. Loads can be controllable or not. A controllable load, such as automatically lighting or the charge of an electric vehicle, is particularly important to Microgrids because it gives a prediction and less load variability.

- **Storage devices** [20]

Storage is very important to assure the continuous access to electricity. As said previously, storage systems are still expensive and increase the overall cost of having an installed Microgrid. Storage devices can include not only electrical storage but also pressure, gravitational and heat storage technologies.

1.4 Levelized cost of energy and storage

The Levelised Cost Of Energy (LCOE) is a method to compare the overall costs of electricity produced from different sources. It is a standardized way to compare completely different sources of energies with each other, from renewable energies to diesel generators.

The formula to calculate the LCOE, takes into account the costs for investment, operation and maintenance, fuel, carbon emissions and decommissioning and dismantling [26]:

$$\text{LCOE} = \frac{\sum[(Capital_t + O\&M_t + Fuel_t + Carbon_t + D_t) * (1+r)^{-t}]}{\sum MWh\ (1+r)^{-t}}$$

Where the different variables are:

MWh	=	The amount of electricity produced in MWh, assumed constant
$(1+r)^{-t}$	=	The discount factor for year t (reflecting payments to capital)
$Capital_t$	=	Total capital construction costs in year t
$O\&M_t$	=	Operations and maintenance costs in year t
$Fuel_t$	=	Fuel costs in year t
$Carbon_t$	=	Carbon costs in year t
D_t	=	Decommissioning and waste management costs in year t

The term of discount rate [27], defines the interest rate you need to earn on a given amount of money today to end up with a given amount of money in the future. It is also a measure of the risk associated with the company or project for capital providers, showing for the assumed risk the return on capital they expect. For this kind of projects, the discount rate can depend on several aspects, such as the loan interests, the saving interest rate, the size of the company, whether you receive or not state subsidies, etc.

There is a different LCOE for different types of solar generation as you can see in [28]:

- Residential
- Commercial
- Community
- Utility scale
- Solar towers

We have chosen the LCOE for Solar Photovoltaics for communities because even if our PV is installed in houses, the battery bank is centralized and the excess power from the panels goes to those batteries and then spreads throughout the MG. Just as LCOE is a method for comparing electricity costs from different sources, LCOS provides an objective methodology for comparing costs and performance of different energy storage technologies. It takes into account **capital**

costs (Engineering-Procurement-Construction, AC Systems and DC Systems), **augmentation costs**, **operating costs** (Extended Warranty, Charging costs and Operations and management costs) and **other costs** (Debt services and taxes). [17]

In the following table, the comparison between the LCOE/LCOS of different technologies.

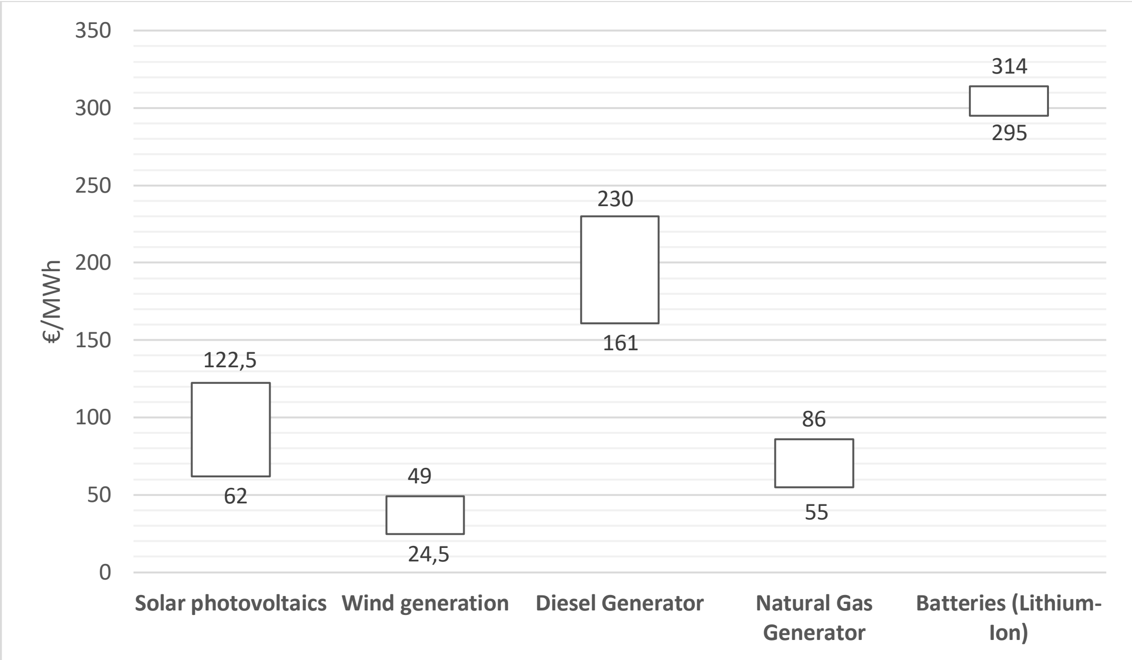

Figure 11: LCOE/LCOS of the equipment [28] [17]

2 Optimization

The objective of this project is to optimize the operation of a Microgrid, meaning that the basis of the project is optimization. That is the reason why a concept must be defined, specifically in the mathematical optimization, then how to apply it to our case of study, a Microgrid and finally, justifying the best optimization software to solve the problem.

2.1 Definition of optimization

The definition of optimization is "finding an alternative with the most cost-effective or highest achievable performance under the given constraints, by maximizing desired factors and minimizing undesired ones." [29]

In an optimization problem, the value of the magnitudes that characterize the configuration of a physical or organizational system and a control rule of the system will be defined in order to minimize or maximize a result that depends on the value of the magnitudes mentioned.

The optimization problems are usually composed of this [30]:

- **Objective function**

  It is the quantitative measure of the performance of the system to be optimized. Some examples of objective functions are, as in this project, the minimization of the costs of operation of a Microgrid, but it could also be the maximization of the benefits of the sale of some products…

- **Variables**

  Represent the decisions that can be taken to affect the value of the target function. As for example in our case, the solar power generation or wind generation or in the sale example, the quantity of each produced and sold product.

- **Restrictions**

  Represent the set of relationships that certain variables are required to satisfy. For example, the maximum and minimum power that our solar panels or wind turbines can generate, or in the case of the sale, the maximum quantity of products that the factory can produce.

There are a few types of optimizations with the following general mathematical expressions:

Linear programming *(LP)*	$[MIN] c * x$ $Ax = b$ $x \geq 0$ $x \in \mathbb{R}^n, c \in \mathbb{R}^n, A \in \mathbb{R}^{m*n}, b \in \mathbb{R}^m$
Mixed integer linear programming (*MILP*)	$[MIN] c * x + d * y$ $Ax + By = b$ $x, y \geq 0$ $x \in \mathbb{R}^n, y \in \mathbb{Z}^t, c \in \mathbb{R}^n, d \in \mathbb{R}^t$ $A \in \mathbb{R}^{m*n}, B \in \mathbb{R}^{m*t}\ b \in \mathbb{R}^m$
Quadratic programming (*QP*)	$[MIN] c * x + \frac{1}{2} x^T Q x$ $Ax = b$ $x \geq 0$ $x \in \mathbb{R}^n, c \in \mathbb{R}^n$ $A \in \mathbb{R}^{m*n}, Q \in \mathbb{R}^{n*n}\ b \in \mathbb{R}^m$
Nonlinear programming (*NLP*)	$[MIN] f(x)$ $g(x) = 0$ $h(x) \leq 0$ $l \leq x \leq u$ $f: \mathbb{R}^n \to \mathbb{R}$ $g, h: \mathbb{R}^n \to \mathbb{R}^m$
Mixed complementarity problem (*MCP*)	$xF(x) = 0$ $x \in \mathbb{R}^n$ $F: \mathbb{R}^n \to \mathbb{R}^n$
Nonlinear programming without restrictions	$[MIN] f(x)$ $f: \mathbb{R}^n \to \mathbb{R}$
Multiobjective programming	$[MIN](f_1(x), \dots, f_k(x))$ $Ax = b$ $x \geq 0$ $x \in \mathbb{R}^n, c \in \mathbb{R}^n, A \in \mathbb{R}^{m*n}, b \in \mathbb{R}^m$ $f_i(x): \mathbb{R}^n \to \mathbb{R}$

Table 3: Optimization types

2.2 Optimization applied to Microgrids

In chapter 1.3, the operation and the structure of a MG as well as the controls (EMS) that ensure a good performance have been studied. The EMS will have to solve the optimization problem.

Depending of the objective and the considerations of the problem, one optimization type or another, from table 3 in the previous chapter 2.1, will be used.

To illustrate the different types of optimization objectives and type, a review of the following papers will be done: [31], [32] and [33].

In [31], the MG consists of PV arrays, batteries, a diesel generator and loads, divided in three sections. The objective of the optimization is to minimize the operating cost of the MG in a time horizon of 24h. Due to the use of continues and discrete variables and non-linear functions, such as the power loss, the optimization problem is a mixed integer non-linear programming (MINLP), which is the same as a NLP with at least one of the variables being an integer.

In [32], the MG consists of PV arrays, wind turbines, batteries, diesel generators, the utility grid and loads. The objective of the optimization is, as the other example, minimizing the cost of the MG in 24h, in five different scenarios. As the previous example, the optimization problem is a mixed integer non-linear programming (MINLP).

In [33], the residential MG consists of a PV module, a micro-wind turbine, the battery of an electric car and the utility grid. The objective of the optimization is minimizing the economic costs associated with the exchanged energy between the utility grid and the MG. A mixed-integer linear programming (MILP) will be the optimization problem, as there are only continuous variables.

In this project, the objective is also minimizing operational costs of the MG. This also means optimizing the optimal operation of the grid to assure the continuity of the electrical supply. The MG is an islanded grid, which includes PV arrays, micro-wind turbines, batteries, auxiliary generators and loads. Due to the considerations in this project, the optimization problem will be a liner programming (LP).

2.3 Optimization software

To optimize a function, it is necessary the use of an optimization tool an optimization software to solve the problem easily. Choosing the right tool is essential to have the most efficient study and solution.

Following, a comparison table between the different optimization software, languages and solvers used in the papers mentioned in the last chapter:

Paper's references	[31]	[32]	[33]
Optimization problem type	MINLP	MINLP	MILP
Software, language	ZIMPL	GAMS	C
Solver	SCIIP	DICOPT, SBB	CPLEX 12.5

Table 4: Overview of optimization languages and solvers used in previous projects

In this project, MATLAB is the optimization tool [34]. Concretely, using Optimization Toolbox, which is a specific application package integrated in MATLAB. The toolbox includes solvers for LP, MILP, QP, NLP, constrained linear least squares, nonlinear least squares, and nonlinear equations. It provides functions for finding parameters that minimize or maximize the objective function while satisfying constraints. The structure of a LP with this language is as follows:

- Creation of the optimization problem:

```
prob = optimproblem('ObjectiveSense','maximize');
```

- Create variables:

```
x = optimvar('x',15,3,'Type','integer','LowerBound',0,'UpperBound',1);
```

- Define the objective function:

```
prob.Objective = sum(sum(f.*x));
```

- Define constraints:

```
onesum = sum(x,2) == 1;
vertsum = sum(x,1) <= 1;
prob.Constraints.onesum = onesum;
prob.Constraints.vertsum = vertsum;
```

- Solve the optimization problem:

```
sol = solve(prob);
```

The reason for choosing this specific software are the basic knowledge about this software learned during the degree course, the ease of importing data from Excel into the MATLAB platform and the plot functions. With one software, treating data, optimizing and displaying the results can be done, which is very comfortable and time-efficient.

3 Case of study

In this chapter, a more detailed analysis of the microgrid will be conducted, explaining the assumptions used for modelling the problem. First, the studied Microgrid will be described and the goal seeked with this study, secondly the external factors of the model will be described.

3.1 Description of the Microgrid

3.1.1 Model description and objectives of the study

The Microgrid of our study is located in Barcelona, Spain. This one, as mentioned before, will be independent of the general source of electricity. Our main goal, as expressed in the chapter 2.2, is to optimize the operational cost of the infrastructure. . Therefore, the cleanness of the energy source will be rewarded and given the fact that the LCOE of the generator isn't too high, a penalization will be imposed.

3.1.2 Weather conditions

The sources of electricity in our model are solar and wind, a study of the potential available in the Barcelona region will be carried out, hence the average radiation and wind speed will be studied.

The PVGIS [35] program not only measures the irradiation for each month, but also provides the inclination that a solar panel should have in order to achieve optimum performance. The results are shown in the following table, as the inclination of the panels cannot be modified every month, solar panels will be installed with the optimum angle for the whole year, 37°. In the following table, the solar radiation each month with that inclination is displayed.

Month	Irradiation on plane at angle 37° $\left[\frac{Wh}{m^2 * day}\right]$	Optimal inclination [degrees]
January	3880	65
February	4850	58
March	6010	45
April	5960	29
May	6460	16
June	6740	8
July	6880	11
August	6580	23
September	5910	39
October	5110	53
November	3970	63
December	3670	68
Annual Average	5510	37

Table 5: Monthly irradiation and optimal angle in Barcelona

As the installation is to work all year round with as few as possible non-renewable source energy consumption, the picked scenario used to base our solar panel dimensioning will be the December.

As grid wind turbines will also be present, the average wind speed and average gust for every month in Barcelona is presented in the next table. As a wind turbine works with the instantaneous wind speed, the gusts will be used.

For the average wind speed and average Gust [36]:

Month	Average Wind Speed (m/s)	Average Gust (m/s)
January	3,5	5,7
February	3,5	5,4
March	3,1	4,6
April	3,3	4,8
May	3,1	4,4
June	3	3,5
July	3	3,5
August	2,5	3,3
September	2,4	3,5
October	2,1	3,2
November	3,2	4,9
December	3,1	5,0
Annual Average	3	4,3

Table 6: Monthly average wind speed in Barcelona

3.2 Scenario

The scenario presented is a network of households, chosen for having the widest range of types of households. The power load consumption for these characteristics was found in the program *Loadprofile* (see ANNEX II). In this program, various types of different profiles are chosen. As the used program is German, this one simulates the behavior of these profiles in a German entourage, their temperatures, consumption… Is it in our knowledge that is it not an ideal approximation, but the study has been followed with these values because of the utility and the amount of information that provides. The results will then be extrapolated to our scenario, Barcelona.

The following figure presents the layout of the households and energy sources. As mentioned operation will be autonomous from the general source of energy and there will be one central battery bank in the node 63, as studied in [1].

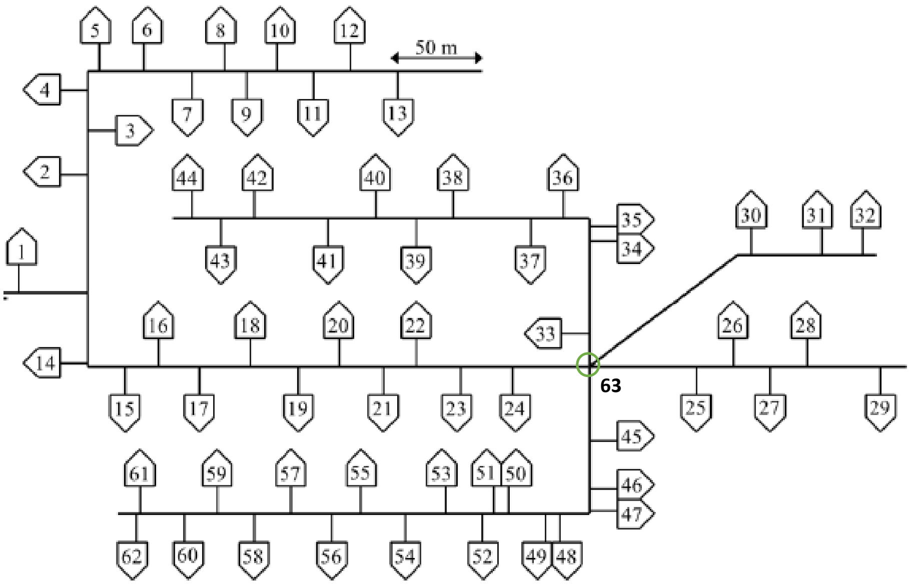

Figure 12: Proposed grid [37]

This grid is made up of 62 homes, in which 12 types of users are distributed. In the following figure, it can be seen the distribution of the different types of users of the grid, and how many users of each type there are.

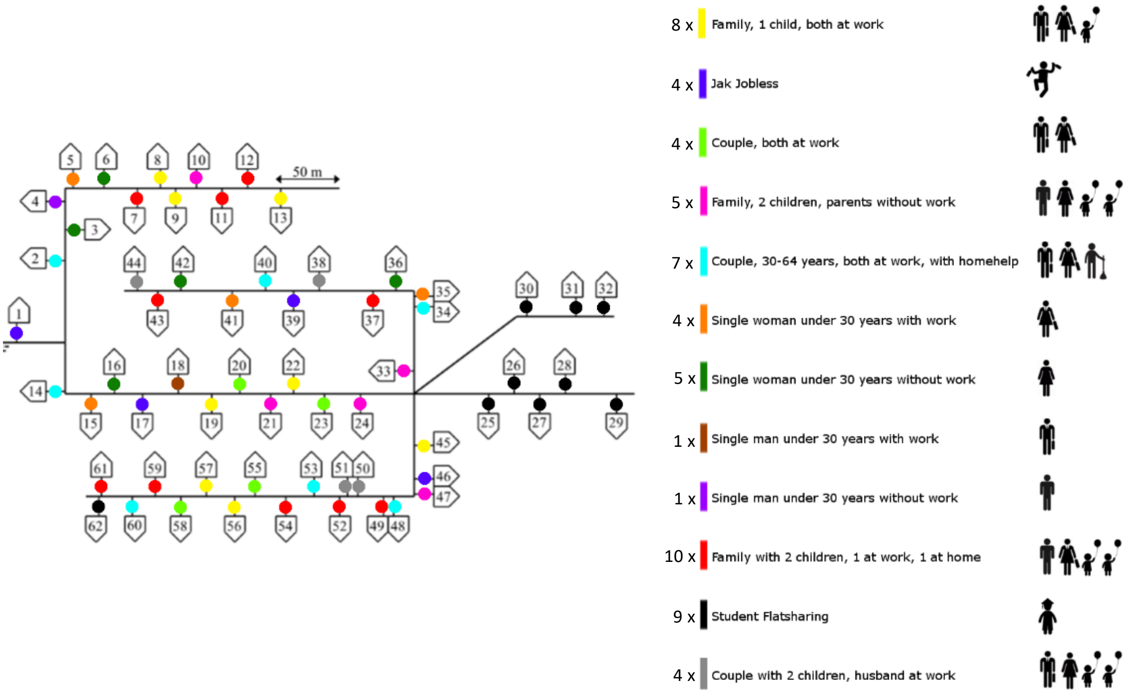

Figure 13: Proposed grid with distribution of households [1]

When dimensioning the generation of renewables, the first step is to decide which renewable source of energy each home has in the network. In the figure below, the generation distribution is schematized. All the houses in our network will have solar generation and only the student flats will have wind generation. This is due to the fact that they are a little separated from the nucleus of houses and therefore:

- More wind reaches the turbines as it is not blocked by the other houses
- In the case of making a little noise, disturb the smallest number of users on the network.

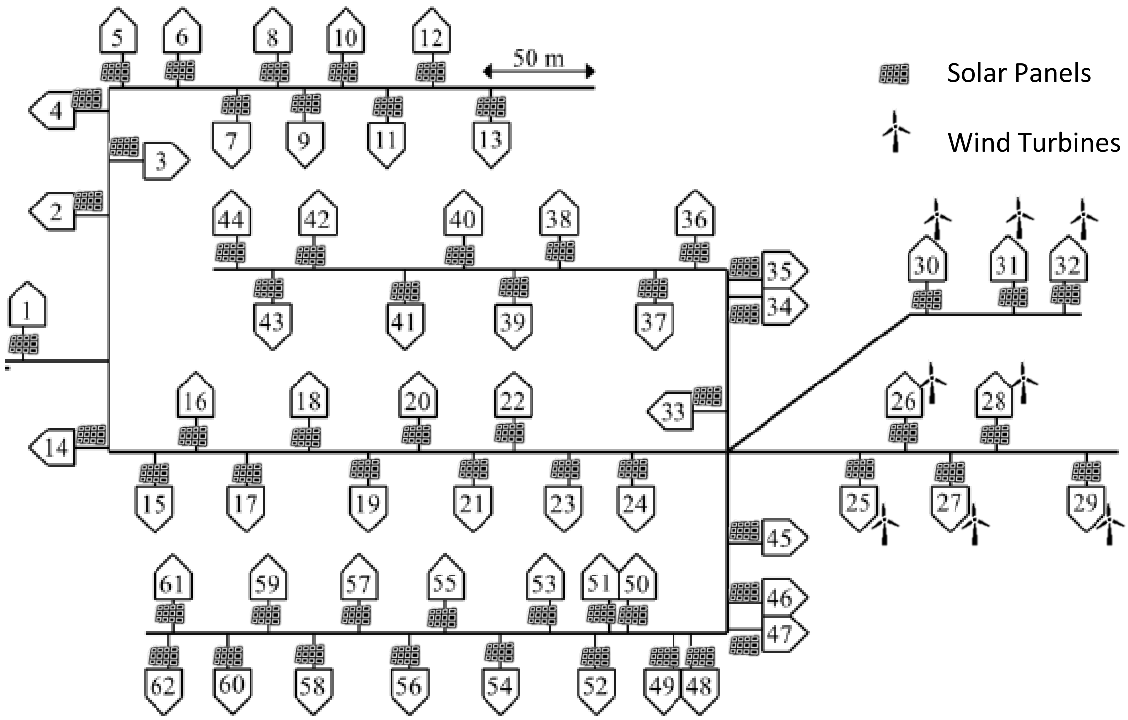

Figure 14: Proposed grid with renewable generation (Own elaboration)

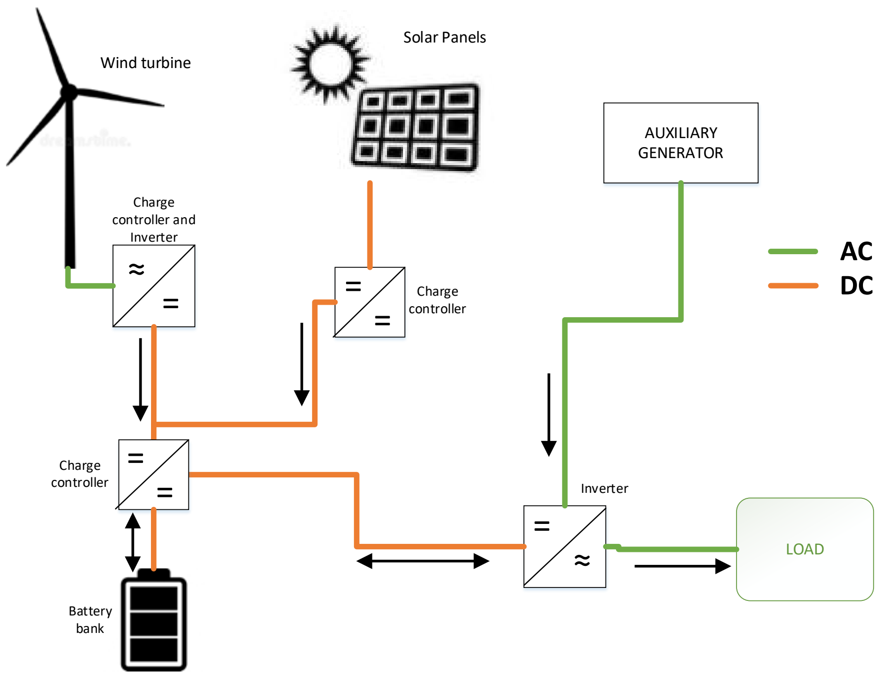

Figure 15: Structure of the equipment (Own elaboration)

In the above figure, an outline of how the network works is presented. As it is a simplified diagram, it is to be noted that there are 62 solar panels and 9 wind turbines evenly distributed, which increases the complexity of the grid. The most important thing to highlight is, as we said in previous chapter 1.3, the need of a Microgrid because for an optimal operation there is a need of an active feed to control bidirectional power flows.

3.3 Justification of the chosen equipment

3.3.1 PV Panels

As it can be seen in table 1 (chapter 1.1.1), Monocrystalline technologies have a longer lifespan and higher efficiency than the other cell technologies. As reliability and security are of important consideration, an off-grid system has been chosen. A higher cost is preferred to be payed in order to have a higher efficiency and longer utility life.

SunPower SPR-E20-327 is one of the most efficient solar panels on the market and with a higher warranty, whereby more reliable.

The technical datasheet of our Solar panel is [38]:

Nominal power	327 W
Panel Efficiency	20,4 %
Rated Voltage (V_{mpp})	54,7 V
Rated Current (I_{mpp})	5,98 A
Power Temp Coef.	-0,35 %/ºC
Voltage Temp Coef.	-176,6 mV/ºC
Current Temp Coef.	2,6 mA/ºC
Temperature	-40 ºC to +85 ºC
Solar Cells	96 Monocrystalline Maxeon Gen II

Table 7 : Technical and Mechanical Data

The chosen PV panels have the following dimensions:

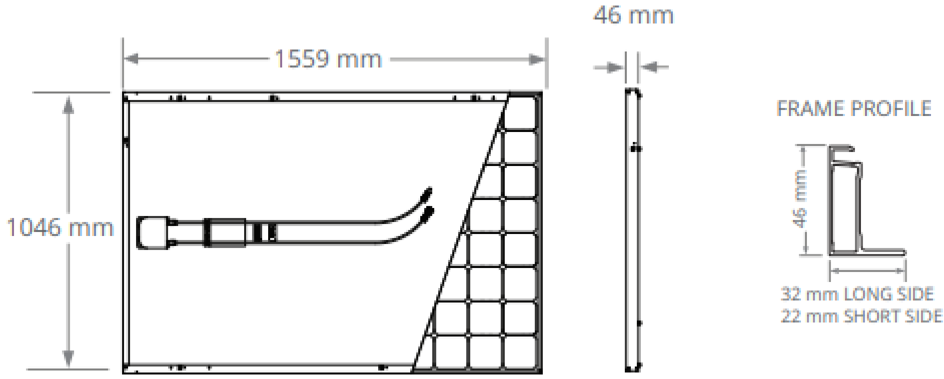

Figure 16: Dimension of the PV panel [38]

3.3.2 Small wind turbines

As shown in table 5, Barcelona is not an especially windy location, which is why one of the most important parameters for choosing a wind turbine is a low start-up wind speed. Another was a high nominal power; most of the small domestic wind turbines have a nominal power of around 1kW. Because of these reasons, the following wind turbine was chosen, ALEKO WG3000 [39].

Rotor diameter	3,2 m
Start-up wind speed	3 m/s
Cut – out wind speed	25m/s
Rated Power	2kW (at 11 m/s)
Peak Power	3kW (at 14 m/s)
Survival Wind Speed	40 m/s

Table 8: Wind turbine specifications

Which has the following power curve for instantaneous wind speeds (full technical specifications and power curve in Annex I):

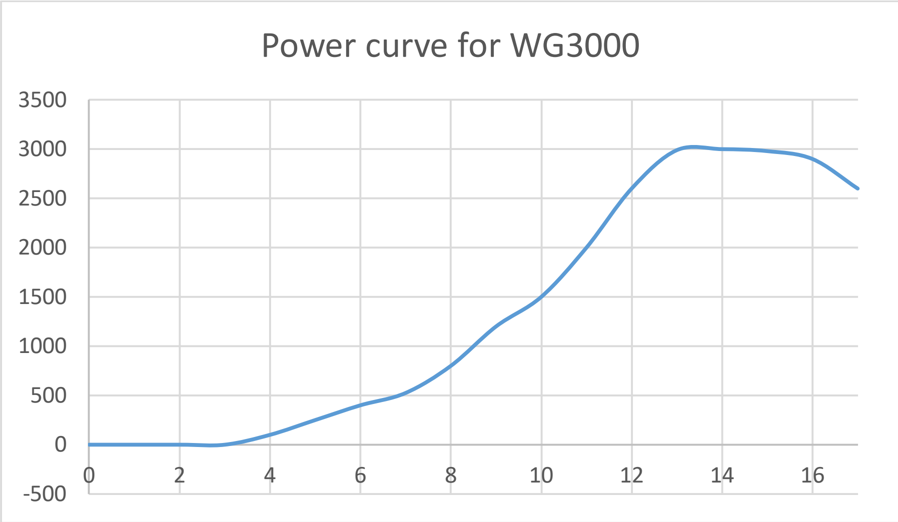

Figure 17: Output power curve for the wind turbine

3.3.3 Batteries

The batteries in the Microgrid have two functions. One function is to act as a backup or UPS system to supply the loads in case of low generation. The second function is to minimize the cost of operation of the Microgrid, by charging the batteries with excess of PV generation or wind power generation, and discharging them to reduce the energy consumed from the auxiliary generators.

The heart of any storage device is the cell. Its quality determines the performance of the entire storage system. Cells provided with a lithium-titanate anode are vastly superior to conventional lithium-ions with regard to capacity, service life and load cycles. [40]

The chosen battery is TiRack from Leclanché, following the technical specifications [41]:

Battery Voltage	510-810 V DC
Operational Current	180 A
Maximum current	300 A
Nominal Capacity	63 kWh
Number of cycles	15 000
DoD	100 %
Temperature range	10º up to 30º

Table 9: Rack specifications

Nominal Capacity	4 200 Wh
Temperature range	0º up to 40º

Table 10: Module specifications

This specific battery has the following characteristics that makes it perfectly suitable for our grid [41]:

- High number of full cycles (15.000), therefore this battery is very suitable for given study case as it reduces maintenance costs and the lifetime is longer and more reliable than regular batteries.
- High speed of charge: 4C (4/h), it takes 15 min. to charge a battery
- 100% Depth of Discharge (DoD)

3.3.4 Auxiliary generators

The chosen supplier of generators [42] has different size of generators:

- 20 – 25 kW
- 35 – 45 kW
- 60 kW
- 70 kW
- 80 – 150 kW

At this stage of the project, a specific one will not be chosen but will be chosen after the optimization because the necessary capacity of auxiliary generators is an open parameter in our optimization problem.

In the following table, you can see specifications of the generators:

Nominal power [kW]	**20**	**25**	**35**	**45**	**60**	**70**	**80**	**100**	**100**	**130**	**150**
Motor [L]	1,5	1,6	2,4	2,4	3,0	6,8	4,6	5,4	6,8	6,8	6,8
Fuel consumption [m^3/h]	8,9	12,5	15,9	20,4	27,2	28,9	31,1	38,9	35,7	50,6	58,4

Table 11: Auxiliary Generator specifications

3.4 Energy generation dimensioning

As seen in the previous chapters, there will be two sources of renewable energy generation, PV panels and Wind turbines. To ensure the continuity of the operation of the installation, batteries and auxiliary generators will also be needed.

3.4.1 PV Panels

To size the surface area of solar panels/ number of solar panels a maximum surface area for each type of user is set. This has been set by the following criteria; there are four types of houses:

- Single-family house (maximum available surface area: 40 m2)
- Large flat (maximum available area: 30 m2)
- Medium flat (maximum available surface area: 20 m2)
- Small flat (maximum available area: 10 m2)

Description of household	Maximum available area [m^2]
Couple, 30-64 years old, both at work with home help	30
Couple, both at work	30
Single woman, under 30 with work	20
Single man, under 30 with work	20
Family, 1 child both at work	40
Couple with 2 children, husband at work	40
Family with 2 children, one at work, one at home	40
Single woman, under 30 without work	10
Single man, under 30 without work	10
Jak Jobless	10
Family, 2 children, without work	20
Student flat sharing	20

Table 12: Resume of the maximum available area for the installation of solar panels per household

The next step will then be to dimension the solar panels to satisfy the consumption of each household as much as possible. The followed methodology is the following (links to the 3 websites), for each household (we will take as an example the case of the family with one child and both parents at work) [43] and [44]:

First, the average power consumption (whole year, 2016 was a leap year) will be calculated:

$$366 * 24 * 60 = 527040 \; [min/year] \tag{3.1}$$

$$Pav = \frac{\sum^{527040} P[kW]}{527040} = 0{,}347941136 \; [kW] \tag{3.2}$$

Then the average power consumption per day:

$$Econs = Pav * 24h/day \approx 8{,}35\ [kWh/day] \quad (3.3)$$

The solar generation will be dimensioned as follows:

- The average power consumption calculated through the whole year (E_{cons} [Wh/day])
- The solar irradiation ($H_{37º}$ [Wh/day.m^2]) for the most disadvantaged month, in our case December as seem in table 4 in chapter 3.1.2.
- HSP (Hours of sun)=Critical month irradiation (December 37º) / 1000 [W/m2] = 3,67 HPS
- The rated output Watt-peak of the chosen PV modules (W_p), in our case W_p=327W
- A coefficient *1.2*, a safety factor to face eventuality and the depreciation of the performance of the different components of the photovoltaic system.
- The area of each solar panel is around 1,63 [m^2] as schematized in figure 15 of chapter 3.3.1.

$$Npv = 1{,}2 * \frac{Econs[\frac{Wh}{day}]}{Wp[W] * HSP[\frac{h}{day}]} = 8{,}35 \approx 9\ solar\ panels \quad (3.4)$$

$$Area = 9 * 1{,}63\ [m2/panel] \approx 14{,}7\ [m2] \quad (3.5)$$

The results for all households are presented in the following table. If the area occupied by the solar panels is greater than the maximal available are for the household, then the maximum number of solar panels that can fit in the available area will be found.

Description of household	**E_{cons} [kWh/day]**	**N_{pv}**	**Area [m^2]**	**Final Area [m^2]**	**N_{pvf}**
Couple, both at work with home help	14,4	15	24,5	24,5	15
Couple, both at work	8	9	14,7	14,7	9
Single woman, under 30 with work	6,4	7	11,4	11,4	7
Single man, under 30 with work	5,9	6	9,8	9,8	6
Family, 1 child both at work	8,4	9	14,7	14,7	9
Couple with 2 children, husband at work	16,4	17	27,7	27,7	17
Family with 2 children, one at work, one at home	16,8	17	27,7	27,7	17
Single woman, under 30 without work	12,7	13	21,2	9,8	6
Single man, under 30 without work	7,5	8	13	9,8	6
Jak Jobless	4	4	6,5	6,5	4
Family, 2 children, without work	13,4	14	22,8	19,6	12
Student Flat-sharing	10,6	11	17,9	17,9	11

Table 13: Number and m^2 of installed solar panels

As the dimensioning of the solar panels for each type of load is done, the following table will summarize the total number of square meters and number of solar panels installed in the network.

#	Description of household	E_{cons} [kWh/day]	E_{cons_total} [kWh/day]	Final Area [m²]	N_{pv_total}
7	**Couple, both at work with home help**	14,4	100,8	196	105
4	**Couple, both at work**	8	32	58,8	36
4	**Single woman, under 30 with work**	6,4	25,6	45,6	28
1	**Single man, under 30 with work**	5,9	5,9	9,8	6
8	**Family, 1 child both at work**	8,4	67,2	117,6	72
4	**Couple with 2 children, husband at work**	16,4	65,6	110,8	68
10	**Family with 2 children, one at work, one at home**	16,8	168	277	170
5	**Single woman, under 30 without work**	12,7	63,5	49	30
1	**Single man, under 30 without work**	7,5	7,5	9,8	6
4	**Jak Jobless**	4	16	26	16
5	**Family, 2 children, without work**	13,4	67	98	60
9	**Student Flat-sharing**	10,6	95,4	161,1	99
62	**Total**	-	714,5	1159,5	696

Table 14: Recapitulation table of the square meters and solar panels of the grid

Having the dimension of solar panels installed in our network and knowing the general radiation for each hour of the day thanks to PVGIS [35], the amount of energy the solar panels generate can be found. Using the following equation:

$$P\ [W] = Irr[W/m^2] * A_{PV}[m^2] *\ K_T \qquad (3.6)$$

With:

- P [W]: Power output
- Irr [W/m²]: Irradiance
- A_{PV} [m²]: Solar panels surface
- K_T [%]: Global efficiency of the PV panel installation

To calculate the global efficiency as in the paper of Marvin Killer, *Impact of Energy Storage Systems in Distribution Grids with high Renewable Energy Penetration* [45], who follows the method of the notes of the course on sizing of installations with batteries [46]:

$$K_T = PV_{eff} * \left(1 - (K_B + K_C + K_R + K_X)\right) * \left(1 - \frac{K_A * D_{out}}{P_{D_{max}}}\right) \tag{3.7}$$

With:

- PV_{eff}: solar panel efficiency, PV_{eff} = 20,4 % (Table 6)
- K_C: inverter losses, K_c = 5%
- K_R: charge controller losses, K_c = 5%
- K_X: additional losses due to joule (cables for example), K_X= 5%

As the batteries are decentralised and not as usual implemented in the solar panels, the following terms concerning them will be disregarded:

- K_B: battery operation losses
- K_A: battery discharge losses
- D_{out}: autonomy days of the installation
- P_{Dmax}: maximum discharge rate

$$K_T = PV_{eff} * \left(1 - (K_C + K_R + K_X)\right) \tag{3.8}$$

$$K_T = 0{,}204 * \left(1 - (0{,}05 + 0{,}05 + 0{,}05)\right) = 17{,}34\% \tag{3.9}$$

In the following table, having the sun irradiation [W/m^2] and using equation 3.6 the power output of the solar panel can be calculated [kW]. This simulation has been done using March data, because it is an average month.

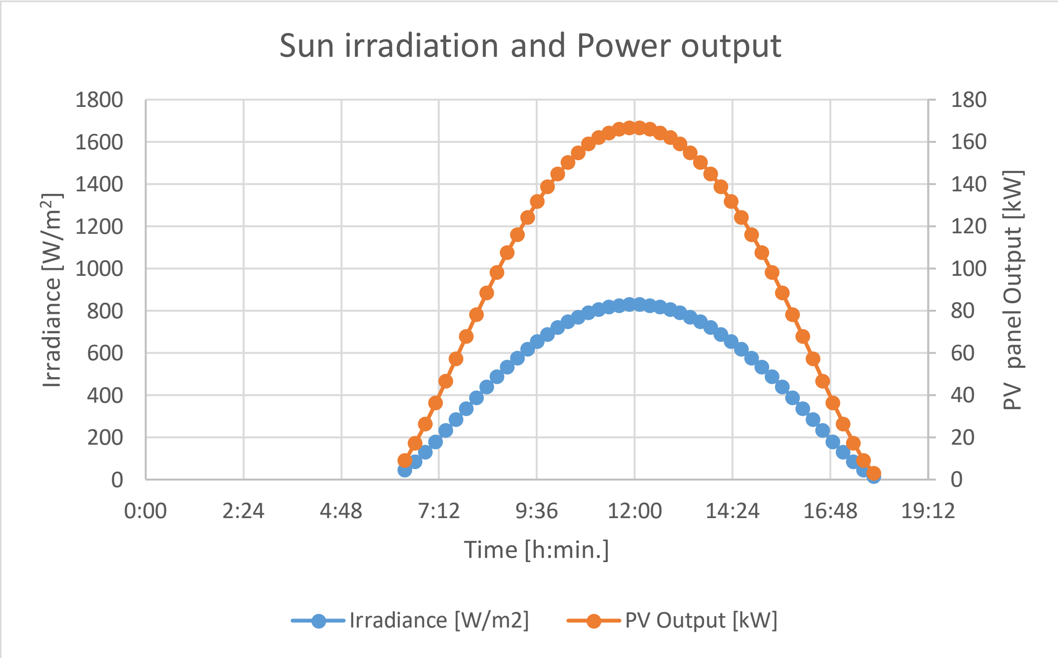

Figure 18: Comparison graphic between irradiance and power output

In the following curve, given by the manufacturer of the solar panels, the radiation effects on the outputs (current and voltage) of the technology can be seen.

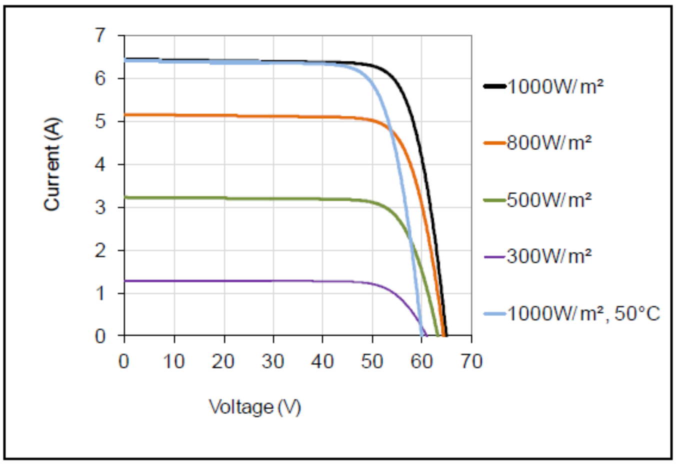

Figure 19: IV Curve for several irradiation values [38]

Solar generation in the nominal value of irradiation (1000W/m^2) will now be studied:

$$PV_{nom}[kW] = PV_{surface} * Irr_{nominal} * Kt \tag{3.10}$$

Results can be seen in table 14.

3.4.2 Wind turbines

It is important to specify that the wind turbines will be dimensioned to generate for covering the consumption of the 9 student flat sharing. Hence, the same equations (3.1, 3.2, 3.3) as the PV panel dimensioning will be used with the data of the student flat sharing. The 9 student flat sharing will be considered as a whole.

First, the average power consumption:

$$366 * 24 * 60 = 527040 \; [min/year] \tag{3.11}$$

$$Pav = \frac{\sum^{527040} P[kW]}{527040} = 3{,}976 \; [kW] \tag{3.12}$$

Then the average power consumption per day:

$$Econs = Pav * 24h/day \approx 95{,}1456 \; [kWh/day] \tag{3.13}$$

The power of the wind can be expressed as [47], [48], [14]:

$$P = \frac{1}{2} \rho A V^3 Cp \tag{3.14}$$

With:

- A [m^2]: area at speed V [m/s]
- ρ [kg/m3]: air density (at 15°C and 1 atm, ρ = 1.225 kg/m3)
- Cp: coefficient of power of rotor, the fraction of the wind's power that is extracted by the blades

Knowing that the area is πR^2, with R, the rotor radius:

$$P = 1/2 \; \rho \pi R^2 V^3 Cp \tag{3.15}$$

Extracted from the technical description of the wind turbine, the nominal generation (at 11m/s) is 2kW. Results of both solar and wind nominal generation are exposed in the following table.

#	Description of household	PV nominal generation [kW]	Wind nominal generation [kW]	Total generation [kW]
7	**Couple, both at work with home help**	4,25	-	29,74
4	**Couple, both at work**	2,55	-	10,20
4	**Single woman, under 30 with work**	1,98	-	7,91
1	**Single man, under 30 with work**	1,70	-	1,70
8	**Family, 1 child both at work**	2,55	-	20,39
4	**Couple with 2 children, husband at work**	4,80	-	19,21
10	**Family with 2 children, one at work, one at home**	4,80	-	48,03
5	**Single woman, under 30 without work**	1,70	-	8,50
1	**Single man, under 30 without work**	1,70	-	1,70
4	**Jak Jobless**	1,13	-	4,51
5	**Family, 2 children, without work**	3,40	-	16,99
9	**Student Flat-sharing**	3,10	2	45,9
62	**Total**	196,81	18	214,81

Table 15: Nominal power of both wind and solar generation

3.4.3 Charge controller

“Solar charge controllers regulate the energy flowing from the PV array and transfer it directly to the batteries as a DC-coupled system, which is the most efficient and effective manner,” Philip Undercuffler, director of strategic platforms at OutBack Power [49].

To avoid damage and overcharge the batteries of our grid, a charge controller has to be installed. To dimension it, the maximum input and output currents of the appropriate regulator for each application will depend on the maximum current that the photovoltaic generation system can produce for the input and the maximum current of the loads for the output. In order to take into account possible irradiance peaks or temperature changes, it is recommended that, when choosing the charge controller, it has to be one with 15-25% higher than the short-circuit current that can reach it from the photovoltaic generation system (I_{input}) or the one that can consume the system load (I_{output}). The choice of the solar controller will be the one that supports the higher of the two calculated currents.

The same is done also for the wind generation system.

The method to dimension the charge controller is as follows [50]:

First the study of which of the currents is higher, the current from the photovoltaic system (I_{input}) or to the charge (I_{ouput}). Or for the case of the wind generation system, the current from the wind turbines or to the charge

First, the I_{input} will be calculated as follows:

$$I_{input} = I_{mod.} * N_{mod.} \tag{3.16}$$

$$I_{mod.} = \frac{W_p * \eta_{mod.}}{V_{mod.}} \tag{3.17}$$

$$I_{input} = \frac{W_p * \eta_{mod.}}{V_{mod.}} * N_{mod.} \tag{3.18}$$

Where:
I_{input}: Current produced by the photovoltaic generation (A)
$I_{mod.}$: Current produced by each parallel branch of the generator (A)
$N_{mod.}$: Number of parallel branches of the generator
W_p: Peak power of the photovoltaic module (W), 327 W in our case
$\eta_{mod.}$: Module Performance, 20,7% for our module
$V_{mod.}$: Nominal voltage of the modules (V)

For the wind generation the equations (3.17) and (3.18) remains the same but the equation (3.16) will be as follows:

$$I_{input} = I_{WT} * \#_{WT} \tag{3.19}$$

Where:
I_{input}: Current produced by the wind generation (A)
$I_{WT.}$: Current produced by each Wind turbine (A)
$\#_{WT.}$: Number of Wind turbines

The intensity consumed by the load is determined taking into account all the consumptions at the same time:

$$I_{LOAD} = \frac{P_{DC}}{V_{BAT}} + \frac{P_{AC}}{220} \tag{3.20}$$

Where:
I_{LOAD}: Load-consuming current (A)
P_{DC}: Load power in DC (W)
V_{BAT}: Rated battery voltage (V)
P_{AC}: Load power in AC (W)

Of these two currents, the maximum of both will be the one that the charge controller will have to stand.

$$I_{CHC} = \max(I_{INPUT}, I_{LOAD}) \tag{3.21}$$

The dimension should be as stated. Nevertheless, as the main purpose of our project is to optimize the operation of the MG, and not to dimension it, the charge controller will not be dimensioned it. However, this doesn't mean that the charge controller is not important and can be neglected in our installation, but the sizing will not be included in the paper.

3.4.4 Inverter

The power inverter is an electronic device that converts the direct current voltage (DC) into a symmetrical alternating current voltage (AC).

The input voltage, output voltage and frequency, and overall power handling depend on the design of the specific device or circuitry. The inverter does not produce any power; the power is provided by the DC source.

To ensure the good performance of the system and to prevent eventualities, the size of the inverter should be a 20% more than the load demand.

As with the charge controller, this device will not be sized either for the same reason, it is not the purpose of the project.

3.4.5 Battery bank

To dimension it the following parameters are needed [50]:

- The maximal depth of discharche (DoD)- 100%
- Days of autonomy (N)

$$C_{bat}[Wh] = \frac{E_{cons\ av.} * N}{DoD} \tag{3.22}$$

With $E_{cons\ av.}$ as eq. (3.2), but for the whole grid:

$$Pav = \frac{\sum^{527040} P[kW]}{527040} = 29{,}75\ [kW] \tag{3.23}$$

Then the average power consumption per day:

$$Econs = Pav * 24h/day \approx 714{,}044\ [kWh/day] \tag{3.24}$$

$$C_{bat} = \frac{714{,}077 * 3}{100\%} = 2142{,}132\ [kWh] \tag{3.25}$$

Knowing that the storage capacity of our battery is 63kWh [41], 35 batteries will be installed. As mentioned in chapter 3.2, the batteries will be installed in one node of the grid (point 63), so further on will consider the 35 batteries as one battery with 2205kWh capacity.

3.4.6 Auxiliary generators

The sizing of the auxiliary generators will not be done at this point of the project as they can be bought and installed very easily and fast. With the output of the optimization problem, the number of natural gas generators will be known.

4 Mathematical formulation of the optimization problem

4.1 Considerations

The following assumptions will be considered for the optimization problem of our Microgrid [51]:

- Power loss in cables is neglected
- Voltage level in all of the points of the MG is the same
- Reactive power flow is neglected

The time horizon considered, T_{sim}, in this work is 24 hours. This period is divided in intervals of time Δt, which in this work are 1-hour intervals. The number of intervals is:

$$N = \frac{T_{sim}}{\Delta t} \tag{4.26}$$

4.2 Objective function

The objective of our optimization is to minimize the cost of the operation of the MG [31]

$$min \sum_{i=1}^{N} (C_{element}\ (i) * P_{element}\ (i)) * t_i \ , \forall element\ \in E \tag{4.27}$$

$$E = \{PV\ Array, natural\ gas\ generators, WTs, battery\ bank\} \tag{4.28}$$

With:

- $C_{element}$ [€/kWh], cost of the operation of this energy LCOE (Chapter 1.3):

  C_{PV_ARRAY}=100€/MWh

  $C_{NATURAL\_GAS}$=80€/MWh

  $C_{WIND\_TURBINES}$=35€/MWh

  C_{BAT}=300€/MWh

- $P_{element}$ [kW], power of the element in the interval i
- i ∈ {1, 2,… ,N}, N = number of intervals
- t_i, time of the interval

The most important constraint that our optimization problem must follow is the one defined below by equation (4.29 and 4.30), for each time step, load and demand have to compensate.

$$D = G\ ,\forall t \tag{4.29}$$

$$D = P_{solar} + P_{wind} + b * P_{battery} + P_{aux}\ ,\forall t \tag{4.30}$$

Where:

- D, demand [kW]
- G, generation [kW]
- b, b=1 when the battery is discharging, b=-1 when the battery is charging an b=0 when the battery charge stays constant (see figure 19)

4.2.1 Solar

The limits of PV generation are between zero and the power generated if the entire surface dimensioned in chapter 3.4.1 is used:

$$0 \leq P_{solar_{1\ldots n}} \leq P_{max_{1\ldots n}} \tag{4.31}$$

$$0 \leq P_{solar_{1\ldots n}} \leq Surf_{TOTAL} * Irr * K_T \tag{4.32}$$

With:

- K_T, efficiency factor, equation (3.9)
- $Surf_{TOTAL}$, Total available solar panel installed surface [m^2]
- Irr, Irradiance every hour [W/m^2]

As Irr depends of external inputs and KT is constant, the variable to optimize is the square meter's surface of solar panels (4.33), which is a constant during all the optimization. The reason to have it as a constant is that once you install this surface of PV panels, it is impossible to uninstall and install every time step. The optimized surface will be the final dimensioning of OV arrays on the MG.

Even though, the equation (4.34) will not appear in the optimization code and that we consider PV arrays as a hole and not like a sum of individual households, it is important to note that the real situation is like it appears in this equation.

$$P_{solar_{1\ldots n}} = Surf * Irr * K_T \tag{4.33}$$

$$P_{solar} = P_{solar_1} * \#_1 + \cdots + P_{solar_n} * \#_n \tag{4.34}$$

With:

- Surf, this is the variable to optimize [m^2]

- n, households, n = 12
- $\#_n$, number of households in the grid of type n

As Irr depend of external inputs and K_T is constant, the variable to optimize is the square meter's surface of solar panels.

4.2.2 Wind generation

Compared to solar generation, wind generation in this MG is minimal. It is also the cheapest source of energy and doesn't have a peak value in a specific time of the day. These are the reasons why wind generation is a source that is going to be used all the time in the optimization.

$$0 \le P_{wind1,..,9} \le P_{max} \tag{4.35}$$

$$0 \le P_{wind1,...9} \le P_{wind_s} * \#_{turbines} \tag{4.36}$$

$$P_{wind1,..9} = P_{wind} * \#_{turbines} \tag{4.37}$$

With:

- $\#_{turbines}$, number of turbines, $\#_{turbines}$= 9
- P_{Winds}, power output from the wind turbine [W], given by the graph on figure 16.

4.2.3 Battery

Even though battery has high operation costs, it's use is essential to store solar energy during peak hours of sun and a low demand. As the chosen battery has a DoD of 100%, the range of use is between 0 and maximum capacity of the battery.

$$0 \le P_{bat_f} \le C_{max} \tag{4.38}$$

C_{max}, maximum capacity [Wh]

The following figure exposes the operational algorithm the battery is going to follow.

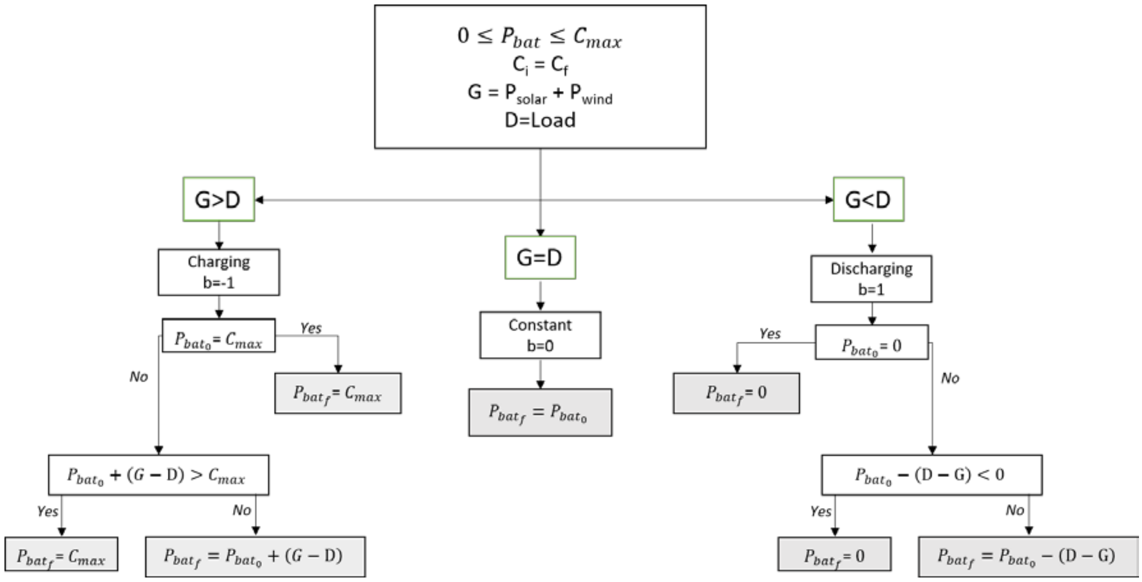

Figure 20: Battery operation structure

To assure a more realistic simulation, the same initial and final conditions will be defined, different for every month. In a month like July with more solar generation for example, it can be anticipated that the battery will be closer to full charge the whole simulation. The chosen initial and final charge rates of the batteries will be as follows:

- 45% Charge in March
- 60% Charge in July
- 30% Charge December

4.2.4 Auxiliary generators

The number of auxiliary generators and it´s power production is an open parameter and will be set after the simulation.

$$0 \leq P_{aux} \leq \infty \tag{4.39}$$

A generator usage fine will be applied, as they are provided with natural gas, which is not a renewable source. The fine will be high enough so the cost of auxiliary generators is higher than batteries.

4.2.5 Load/ Demand

The energy consumption of each household, as mentioned earlier in the project, is downloaded from the Load Profile Generator program. The program expresses the consumption in *Wh/min*. In order to use this data, a program to treat the data and gave us the *Watts* every hour had to be developed.

For this purpose, MATLAB was used, in which inserting the Excel file, the simulation days to have the demand data, and the output was a matrix with, the hours in the first column and the energy consumption in the second and a plot of the demand (Energy consumed). This program explanation is explained in Annex II.

5 Analysis of the results

5.1 LOAD vs SOLAR AND WIND POWER

In a first step, a simulation has been done with load consumption data and with solar generation and wind generation power output using the full capacity of the renewable sources. This simulation has been done with the program MATLAB and the code LOAD (see ANNEX III) and for three different months, March as having average generation, July as the month with more solar generation and finally, December with a higher wind generation but the lowest PV generation. Results are presented in this three following figures:

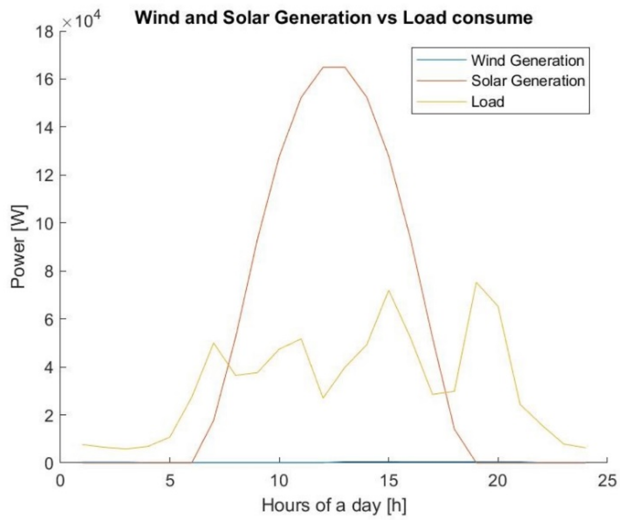

Figure 21: March wind and solar generation vs load consume

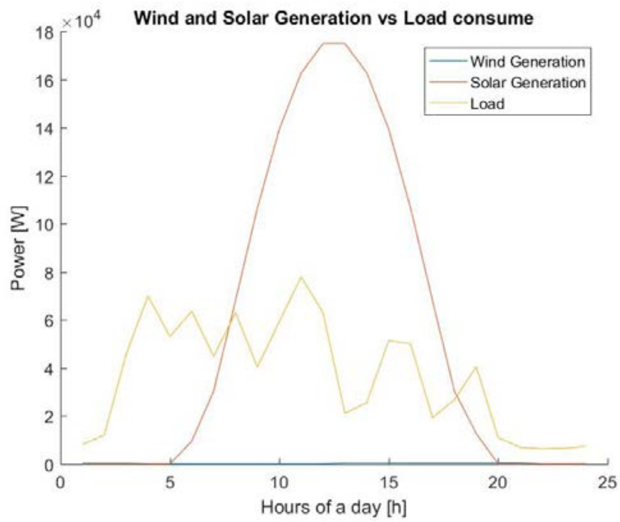

Figure 22: July wind and solar generation vs load consume

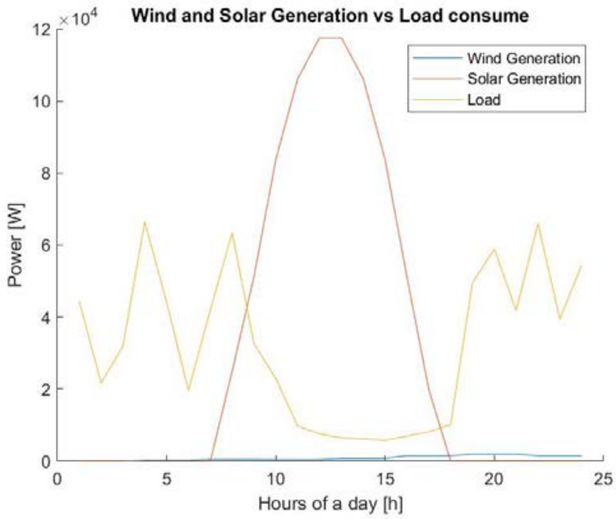

Figure 23: December wind and solar generation vs load consume

5.2 Optimization results

After doing a first simulation of the dimensioned capacities for every source of energy compared with the load consumption, the next step was to simulate and optimize this results for three different times of the year.

5.2.1 March

March was chosen to be a random month with an average generation, as explained in the previous chapter. The objective function of this optimization was to minimize costs of operation, the value of the operating costs during an average day in March are **269,0381€**. This is the less expensive month, compared to July and December, the other two months when we did a simulation. Following, there is a picture of the use of every source of energy. Please note that the battery takes negative values because this graphic displays changes in the charge of the batteries. It is important to clarify this, due to the characteristics of a battery operating between 0 and C_{max}.

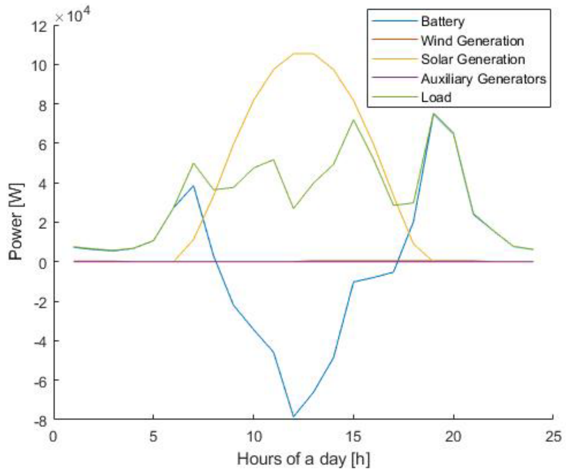

Figure 24: Optimization results for March

Even if wind generation has not a lot of potential, as is it the least expensive source, the use of this source was of a 100%. In the following table, a recapitulation of the most important results of the optimization, as well as the percentage of what was already dimensioned. Please note that, maximal and minimal capacity battery are nor very high or very low.

	Data	Percentage
Needed surface of solar panels [m²]	741,1126	64%
Number of wind generators	9	100%
Auxiliary generators	0	-
Max Capacity battery [kWh]	1205,7	55%
Min Capacity battery [kWh]	886,88	40%
Total Costs [€]	269,04	-

Table 16: Resume of the optimization output

5.2.2 July

July is the month with more solar radiation due to long and the high percentage of sunny days. However, this month's wind generation is minimal. The objective function of this optimization was to minimize costs of operation, the value of the operating costs during an average day in July are **286,31€**, which are slightly higher than costs in March. Following, there is a picture of the use of every source of energy.

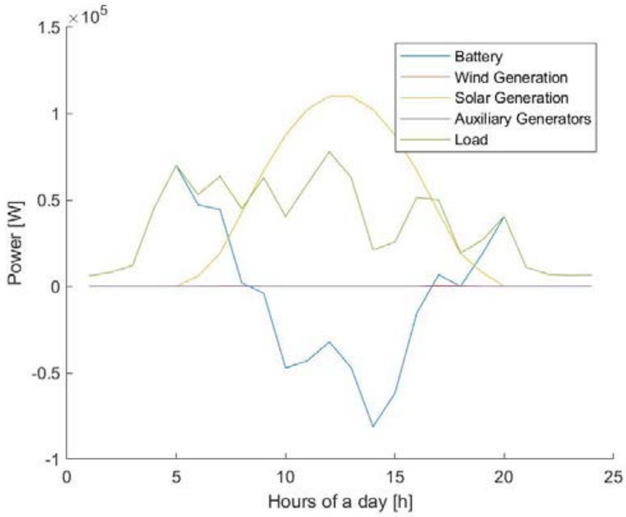

Figure 25: Optimization results for July

In the table below, the summary of optimization results is shown. The surface of solar panels needed is slightly smaller to the same parameter in march. It is important to remind that battery initial and final conditions for this month were a 60% of total capacity of the batteries. Then, capacity values fluctuate between a 49% and a 64% which is predictable and appropriate.

	Data	Percentage
Needed surface of solar panels [m²]	728,61	63%
Number of wind generators	9	100%
Auxiliary generators	0	-
Max Capacity battery [kWh]	1419,8	64%
Min Capacity battery [kWh]	1087,9	49%
Total Costs [€]	286,31	-

Table 17: Resume of the optimization output

5.2.3 December

December is the month with the least solar radiation due to short and the low percentage of sunny days, completely the opposite as July´s statements. However, this month's wind generation is maximal. The objective function of this optimization was to minimize costs of operation, the value of the operating costs during an average day in December are **444,3€**, which is significantly higher than March and July. It is understandable due to the fact that batteries have a wider use and they are the most expensive source. Following, there is a picture of the use of every source of energy.

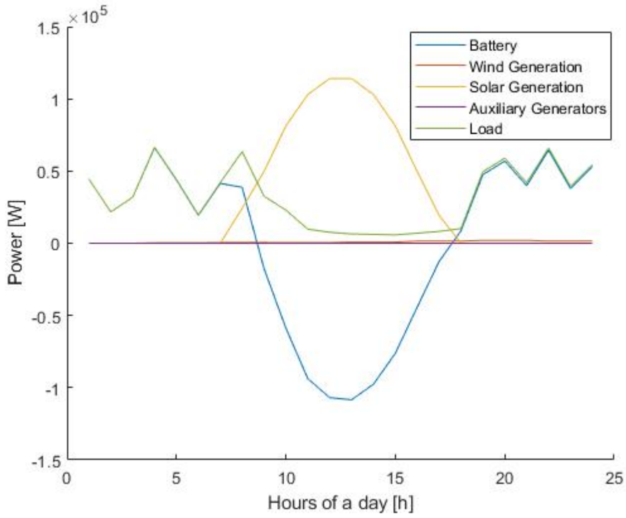

Figure 26: Optimization results for December

In the table below, the summary of optimization results is shown. The needed surface of solar panels is 1124,9 m^2, which is significantly higher than March (52%) and July (54%). Also the use of the battery is higher, note that initial and final charge conditions in December are a 30% of total battery capacity.

	Data	Percentage
Needed surface of solar panels [m^2]	1124,9	97%
Number of wind generators	9	100%
Auxiliary generators	0	-
Max Capacity battery [kWh]	969,9	44%
Min Capacity battery [kWh]	353,88	16%
Total Costs [€]	444,3	-

Table 18: Resume of the optimization output

5.3 Final dimensioning of the Microgrid

After studying optimization results in three months, March, July and December. A final decision has to be made to dimension the MG.

First of all, it is important to note that the MG of this study is an autonomous Microgrid, islanded from the general grid. This is crucial for making a decision, as the grid must assure the continuity of power supply. This is the reason why results from the December optimization are taken to finalize the design of the MG.

PV panels

A surface of 1124,9 m^2 has been the result of the optimization. As seen in figure (16), the area of a chosen PV panels is 1,63m.

Then, **691 PV panels** will be installed in the MG with a total surface of **1126,33 m^2** and a nominal power output (see equation 3.10) of **195,31 kW.**

Wind turbines

As seen in the optimization's results, wind turbine potential in our grid is very low but as it is the least expensive source of energy, all of the installed potential was used.

Resulting in the installation of the **9** wind turbines with a nominal power output of **18kW**.

Battery bank

The maximum battery capacity was dimensioned as 2205kWh. In the optimization analysis, the battery charge fluctuated from **16%** to **64%** of the total battery capacity. Even if in this analysis, not all the charge capacity was used, for safety reasons and prevent problems in case of a voltage drop, the **2205kWh**, **35 batteries** will be installed.

Auxiliary generator

As displayed in the last 3 tables (Table 16, 17 and 18), auxiliary generation was not needed in any case. But this is yet very important, as large battery margins, to assure power continuity in case of a voltage drop. The installed capacity of auxiliary generators will be a 20% of a day generation, **5** auxiliary generators with a nominal capacity of **150kW** and **one** with **35kW** will be installed (see table 11), with a total nominal generation capacity of **785kW**.

6 Economic study

Energy projects are subject to multiple external and internal economic factors that drive their feasibility and profitability, these will be briefly studied and analyzed in this chapter. Firstly, an external factor discussion will be conducted based on four areas, being: economic output, energy consumption, renewable sources penetration and investment drivers. Then the profitability of the case study will be calculated based on elements such as investment cost, operating costs and fixed costs.

6.1 Macroeconomic analysis

6.1.1 Economic output drivers

The profitability of energy investment projects is largely dependent on the overall health of the economy, its trend and its expected forecast. In order to be able to forecast the overall economy over the next 20-25 years a deeper analysis into the drivers of economic output must be undertaken. Some of the most important drivers will now be discussed.

Gross Domestic Product (GDP)

GDP is a primary indicator of the economic stability and growth prospect, it represents the value of all goods and services produced in a period, and hence may be used as a proxy to measure the size of a country or group of countries economy. GDP has been selected as there´s a positive correlation between GDP and energy consumption, and as seen in the next figure:

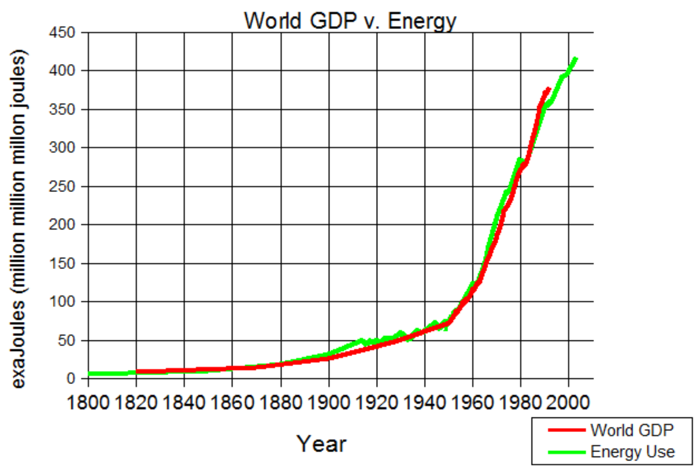

Figure 27: World Energy versus world GDP [52]

As seen in the following table, both US, EU and Spain in particular have positive growth GDP expectations, hence it can be reasonable to assume that energy consumption will also increase given the positive correlation between both variables.

GDP Real Growth	2017	2018	2019	2020	2021	2022
Spain	3,1%	2,8%	2,2%	1,9%	1,7%	1,7%
US	2,3%	2,9%	2,7%	1,9%	1,7%	1,5%
EU	2,7%	2,5%	2,1%	1,8%	1,7%	1,7%

Table 19: GDP Real Growth in Spain, U.S., EU [53]

Inflation Rate

The inflation rate is another key element to analyze as it shows the price variation of the goods and services of a country and is measured by the CPI index, the CPI index studies this price variation for a basket of representative goods in which energy is included. It can be reasonably concluded that movements in the CPI index will incur movements in the energy prices and vice versa, in the following table the CPI index forecast for the US, the EU area and Spain are shown.

Inflation rate	2017	2018	2019	2020	2021	2022
Spain	2%	1,7%	1,6%	1,7%	1,8%	1,9%
US	2,1%	2,5%	2,4%	2,1%	2%	2,1%
EU	1,7%	1,9%	1,8%	1,9%	2,1%	2,1%

Table 20: Inflation rate in Spain, U.S., EU [54]

European Consumer Confidence Index

The Consumer Confidence Index (CCI) measures consumer short term feelings about the future economy. As a rule of thumb, if consumers are optimistic they will increase consumption and spending, stimulating the economy and demand of energy. As seen in the following figure, after the economic crisis the EU CCI index dropped to minimum levels and since then it has had a rising tendency.

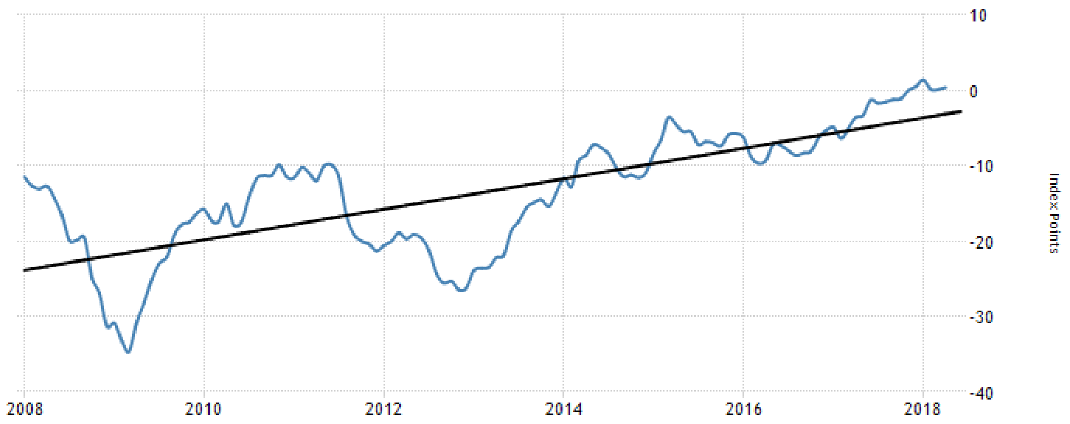

Figure 28: EU Consumer Confidence Index 2008-2018 [55]

6.1.2 Energy consumption drivers

Another important part of our analysis must focus on the energy consumption forecast, in order to do that several indicators will be studied which prove that energy consumption is going to increase worldwide.

Worldwide population forecast

Energy consumption is tightly correlated to worldwide demographics, hence given a worldwide demographics increase, energy consumption will most probably also increase. This is due to more persons using devices that feed themselves with energy. The following figure shows the expected growth per continent until 2100, it is to be noted that the concern of this study is until 2050 approximately.

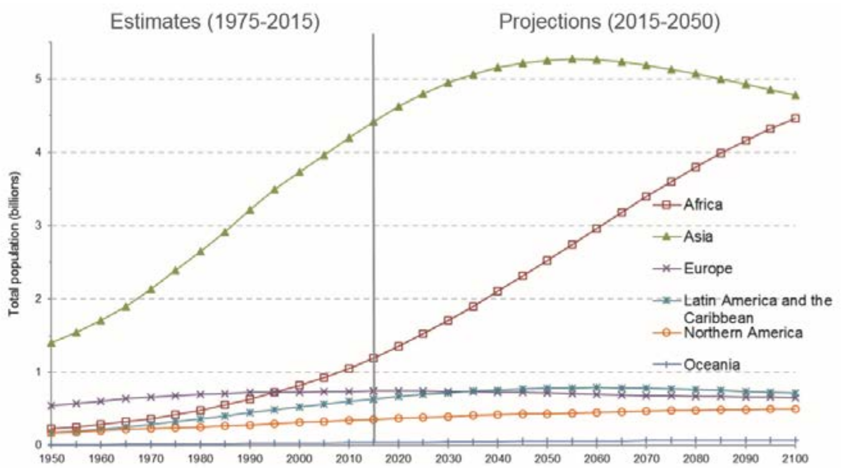

Figure 29:Levels and trends of the world's population by region [56]

Energy consumption per capita

Energy consumption per capita has for the last years organically increased (when not affected by an economic crisis), this tied to an increase in worldwide demographics shows that it can be expected that total energetic output will increase in the foreseeable future. The following figure shows the historic trend and future projection of energy consumption per capita for different countries and regions, it is to be noted that worldwide per capita consumption (red line) has increased steadily, and is expected to continue to do so.

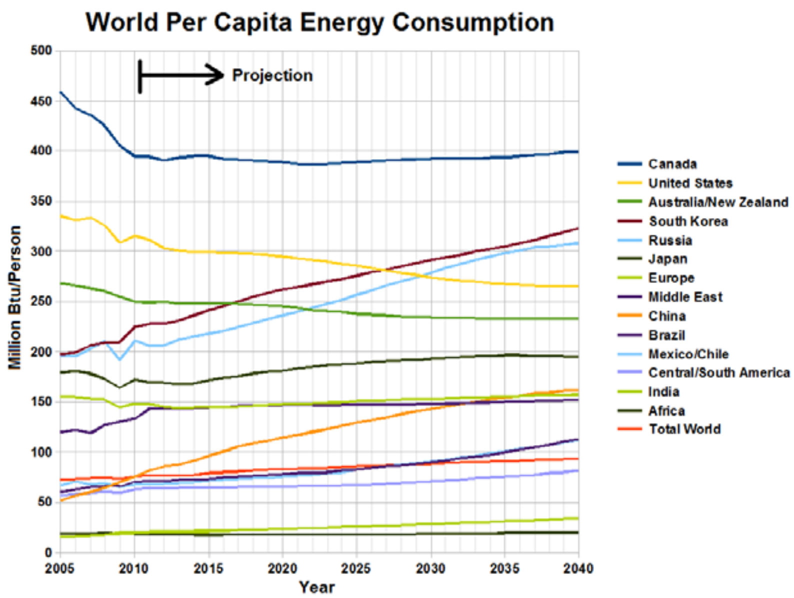

Figure 30: World per capita energy consumption [57]

Technology and living standards

Living quality standards are steadily increasing, as society is more conscious of the outrageous unfairness of wealth distribution in the world, these are having double digit growth rates in emerging economies while moderately increasing in developed economies. This increase has been propelled by the reduction in cost of technological devices (ranging from low consumption lamps to mobile phones), allowing for increased penetration of such products in historically non-developed countries. As a result, more devices need to be charged and powered driving an increase in energy demand. However, it must be noted, that technological advances are a two-sided coin, hence having a detrimental characteristic with respect to energetic consumption, which is the increased efficiency and lower consumption of modern hardware, however it is this author´s belief that this effect will not be as notable as the increased penetration effect.

6.1.3 Renewable energy drivers

In this modern world where energy demand is inevitably increasing, there's a worldwide trend, powered greatly by the European Energy Commision, to increase greatly the share of renewable energies in the total world output.

This trend has motivated the adoption of several worldwide and region based renewable policies which set an upper limit on the amount of emissions allowed per firm and industry as well as target percentages of renewables contribution to the total mix.

Drivers for renewable energy innovation in the EU are [58]: Government spending on research and development, incentive (feed-in) tariffs, investment incentives, tax measures, voluntary programs, obligations and renewable energy certificates.

Feed-in tariffs are a guaranteed price forced by the energy authority so that energy distributors agree to feed in from renewable sources at fixed prices which depend on the nature of the source. Investment incentives are capital allowances aimed at reducing the capital cost of renewable adoption. Tax measures refer to exemptions and benefits related to the consumption of renewable energy. Voluntary programs are adopted by public entities (i.e. national or regional governments) to boost renewable energy consumption. Obligations refers to the minimum legal percentage of energy produced that needs to be renewable. Finally, certificates are carbon footprint allowances in line with a quota system.

As mentioned the EU is a pioneer on the renewable energy adoption plan, its "Horizon 2020" program [2] sets a target renewable energy contribution of 20% to the final energy consumption. Beyond 2020 EU countries have agreed a 27% target. The EU has also established a 2050 roadmap which focuses on an 80% CO_2 emissions.

6.2 Economic viability

To study economic viability, 6 steps will be followed:

- First of all, the price of energy in the central network in a year is assumed as the revenue of our project (**17.541,9€**), as it is the amount of money the consumers save by not being connected to the grid.
- Then, the variable operability costs are calculated. The variable costs are 0, as neither solar, wind generation and battery have it. Auxiliary generators do have these costs, but as shown in the chapter 5.3, no auxiliary generator will be used, they are installed for safety reasons.
- However, fixed operability costs are different of zero as they evaluate the costs of the installed capacity. In the following table, fixed costs for each technology for a year with the installed capacity in this grid:

Technology	PV generation	Solar generation	Auxiliary Generator	Battery	Total
Fixed costs [€]	1401,003	2.240,194545	11183,445	72,26226	**14.896,9**

Table 21: Fixed costs for each technology and total

- Therefore, the installation has annual benefits of **2.645€**.
- An evaluation of the yearly cash flows will be done through the perpetuity model. Their present value is **29.483,46€** at a discount rate (Weighted Average Cost of Capital) of 7.5%. However, initial installation costs are very high due to many reasons. These technologies are still new and expensive to install and an oversizing is necessary to assure the continuity of the power supply as it is an islanded MG. So, initial costs are higher than the present value of the perpetuity. The NPV of our grid is then negative which allow us to conclude that this investment would not make economic sense.

Hence, the conclusion is that our system is not economically viable.

To have an economically viable system, one of the actions to take will be not installing technologies such as excess battery capacity and auxiliary generators to ensure system safety, but that's not suitable for an island mode system. Also a further analysis on government subsidies should be conducted.

6.3 Budget

6.3.1 Project

An economic study has to be done in an engineering project. The costs applicable to this project are: Human resources, taking into account the worked hours (Table 16) and material costs, material used for the right development of the project (Table 17). Adding the VAT of a 21 %, the total budget is displayed in Table 18.

Tasks	Cost (€/h)	Hours (h)	Total cost (€)
Planning and research	30	100	3.000
Dimensioning of the MG	30	150	4.500
Optimization	30	120	3.600
Drafting the project	20	70	1.400
TOTAL	**-**	**440**	**12.500**

Table 22: Costs for Human resources

In this first table, an overview of the main steps of this project and the time spent in each activity even though they mixed in some occasions.

Tasks	Total cost (€)
MATLAB (with Optimization Toolbox)	69
Office Pro 2016	539
Visio Pro 2016	739
TOTAL	**1.347**

Table 23: Costs of Material

In this other table, from Office Pro 2016, nearly all of the programs of the package were used, Microsoft Word, Microsoft PowerPoint, Microsoft Excel and installed Visio Professional 2016 too. Then, MATLAB was essential for this project and also was the Optimization Toolbox, which was included in the MATLAB + Simulink Student Package.

Tasks	Total cost (€)
Human resources	12.500
Material Costs	1.347
Subtotal	**13.847**
VAT (21%)	2.907,9
TOTAL	**16.754,9**

Table 24: Total budget of the project

To finish with this Chapter, the total budget of this project was **16.754,9€.**

6.3.2 Installation

The installation budget is as follows with the value of the chapter 5.3:

Technology	Cost (€/kW)	Nominal power (kWh)	Total cost (€)
PV Panels	2.074,1	195,3	405.071,7
Wind Turbines	1.167,5	18	21.015
Auxiliary Generation	716,9	785	562.766,5
Batteries	510	2205	1.124.550
TOTAL	**-**	**3.203,3**	**2.113.403,20**

Table 25: Total installation costs

The total installation costs for the technologies in our MG are **2,1 Million €.**

7 Conclusion

Methodology

This chapter is an overview of the performed tasks during this project.

1. An overview study of the existing technologies and solutions in an islanded MG was conducted.
2. A study of a defined MG with different households and real consumption data and with real meteorological data was done.
3. Knowing what is valuable in the studied grid, the most suitable equipment to meet the requirements was chosen.
4. With real consumption data and the technologies to use, each renewable technology was sized.
5. In order to minimize operation costs and assure a good performance of the MG, a code was created.
6. A simulation study of three representative months (in an average month, the worst case and the best case) was conducted.
7. Considering the needs of the consumers and wanting the safest MG possible, a decision on the final sizing of the system was taken.
8. During the simulation, the energetically viability was confirmed, but then a viability economic study was performed.

Conclusions

The study of this installation has resulted in the fact that it is energetically feasible but not economically.

The studied MG is composed of 62 load points, different households with 12 different types of consumers. The chosen renewable technologies were solar generation (present in all 62 households) and wind generation (only present in 9 households). Also to ensure power continuity and enforce safety of the network, centralized batteries and auxiliary generators were installed.

After having performed the simulation in three different months, the most unfavorable (December) case was chosen to ensure the good performance of the grid all year long. The final system counts with **691** solar panels, **9** wind turbines, **35** batteries and **6** auxiliary generators (5 big ones and one smaller one). With a total nominal power of **3,2 MWh.**

Finally, an economical study has been performed showing the non-feasibility of the project. This is due to high installation costs.

Limitations and further considerations

To ensure a more reliable study, the following steps should be taken:

- A full study of governmental subsidies on renewable technologies
- An intensive research on tax regulation on the components of the grid
- Evaluate if nowadays an islanded mode MG is cost-effective or if it's better to have a switch to sell and buy energy from the central grid
- Simulate the project with power losses in the cables of the MG
- Simulate the project with reactive loads

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ANNEX I: Datasheets of the components of the grid

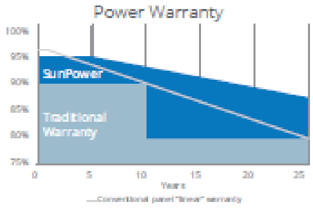
Technical specifications	
Rack specifications	
String format	19" triple rack
Battery modules in series	15
Battery voltage	510 – 810 V DC
Operational current (2C/2C)	180 A
Maximum current per string	300 A
Nominal capacity	63 kWh (C/10)
Specified number of cycles (1C/1C; 23°C; 100% DOD)	up to 15.000
Dimension (HxWxD)	2300 x 1800 x 600 mm
Weight	1800 kg
Temperature range	10°C up to 30°C

Table 26: Rack Specifications

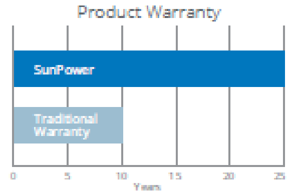
Module specifications	
Cells	Leclanché 936C08 Titanate
Architecture	60 cells; 3 parallel 20 serial
Capacity	4.200 Wh (C/10)
Nominal voltage	46 V
Voltage range	34,0 - 54,0 V
Nomincal current (1C)	90 A
Maximum current	300 A
Cycles	15.000 (100% DoD at room temperature)
Temperature (operation)	+0ºC to +40ºC
Humidity	< 95 % (non condensing)
Dimensions (WxHxD)	463 x 356x 550 mm
Weight	99 kg
Protection class	IP20
Certification	CE, UN 38.3, IEC 61010

Table 27: Module specifications

SunPower Offers The Best Combined Power And Product Warranty



More guaranteed power: 95% for first 5 years, –0.4%/yr. to year 25[7]



Combined Power and Product defect 25-year coverage[8]

Electrical Data

	SPR-E20-327	SPR-E19-320
Nominal Power (Pnom)[11]	327 W	320 W
Power Tolerance	+5/–0%	+5/–0%
Avg. Panel Efficiency[12]	20.4%	19.9%
Rated Voltage (Vmpp)	54.7 V	54.7 V
Rated Current (Impp)	5.98 A	5.86 A
Open-Circuit Voltage (Voc)	64.9 V	64.8 V
Short-Circuit Current (Isc)	6.46 A	6.24 A
Max. System Voltage	1000 V IEC & 600 V UL	
Maximum Series Fuse	15 A	
Power Temp Coef.	–0.35% / °C	
Voltage Temp Coef.	–176.6 mV / °C	
Current Temp Coef.	2.6 mA / °C	

REFERENCES:
1 All comparisons are SPR-E20-327 vs. a representative conventional panel: 250 W, approx. 1.6 m², 15.3% efficiency.
2 Typically 7–9% more energy per watt, BEW/DNV Engineering "SunPower Yield Report," Jan 2013.
3 SunPower 0.25%/yr degradation vs. 1.0%/yr conv. panel. Campeau, Z. et al. "SunPower Module Degradation Rate," SunPower white paper, Feb 2013; Jordan, Dirk "SunPower Test Report," NREL, Q1-2015.
4 "SunPower Module 40-Year Useful Life" SunPower white paper, May 2015. Useful life is 99 out of 100 panels operating at more than 70% of rated power.
5 Second highest, after SunPower X-Series, of over 3,200 silicon solar panels, Photon Module Survey, Feb 2014.
6 8% more energy than the average of the top 10 panel companies tested in 2012 (151 panels, 102 companies), Photon International, Feb 2013.
7 Compared with the top 15 manufacturers. SunPower Warranty Review, May 2015.
8 Some restrictions and exclusions may apply. See warranty for details..
9 5 of top 8 panel manufacturers tested in 2013 report, 3 additional panels in 2014. Ferrara, C., et al. "Fraunhofer PV Durability Initiative for Solar Modules: Part 2". Photovoltaics International, 2014.
10 Compared with the non-stress-tested control panel. Atlas 25+ Durability test report, Feb 2013.
11 Standard Test Conditions (1000 W/m² irradiance, AM 1.5, 25° C). NREL calibration Standard: SOMS current, LACCS FF and Voltage.
12 Based on average of measured power values during production.
13 Type 2 fire rating per UL1703:2013, Class C fire rating per UL1703:2002.

Tests And Certifications

Standard Tests[13]	IEC 61215, IEC 61730, UL1703 (Type 2 Fire Rating)
Quality Certs	ISO 9001:2008, ISO 14001:2004
EHS Compliance	RoHS, OHSAS 18001:2007, lead free, PV Cycle, REACH SVHC-163
Sustainability	Cradle to Cradle Certified™ Silver
Ammonia Test	IEC 62716
Desert Test	10.1109/PVSC.2013.6744437
Salt Spray Test	IEC 61701 (maximum severity)
PID Test	Potential-Induced Degradation free: 1000 V[9]
Available Listings	TUV, UL, JET, MCS, FSEC, CEC

Operating Condition And Mechanical Data

Temperature	–40° C to +85° C
Impact Resistance	25 mm diameter hail at 23 m/s
Appearance	Class A
Solar Cells	96 Monocrystalline Maxeon Gen II
Tempered Glass	High-transmission tempered anti-reflective
Junction Box	IP-65 Rated, MC4
Weight	18.6 kg
Max. Load	Wind: 2400 Pa, 244 kg/m² front & back Snow: 5400 Pa, 550 kg/m² front
Frame	Class 1 black anodised (highest AAMA rating)

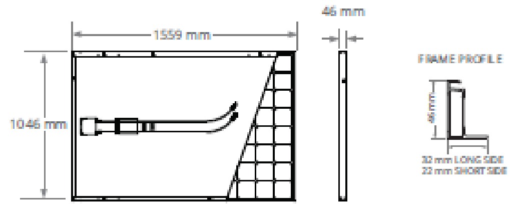


Figure 31: PV Panels Datasheet

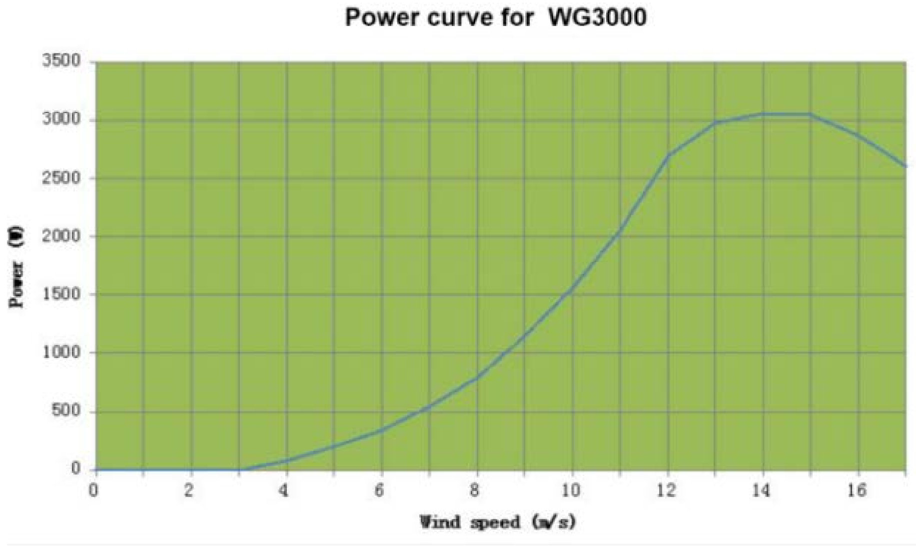


Figure 32: Power curve for wind turbine

Technical specification	
Performance	
Rated power	2000W @11m/s
Peak power	3000W
Start-up wind speed	3m/s
Working wind speed	3.5-25m/s
Survival wind speed	40m/s
Rotor	
Rotor diameter	3.2m
Swept area	8.04m^2
Blade	3pcs reinforced fiber glass
Blade length	154cm
Shell material	precision steel
Rated RPM	380
Weight	75KG
Others	
Generator type	3-phase AC PM, gearless
Speed regulation & protection	yawing + electromagnetic brake
Rated voltage	DC 48-300V
Suggested battery capacity	4pcs 200AH/12VDC
Tower type	6~12m guyed cable / 7~15m free standing
Working temperature	-40-60℃

Table 28: Technical specification of our wind turbine

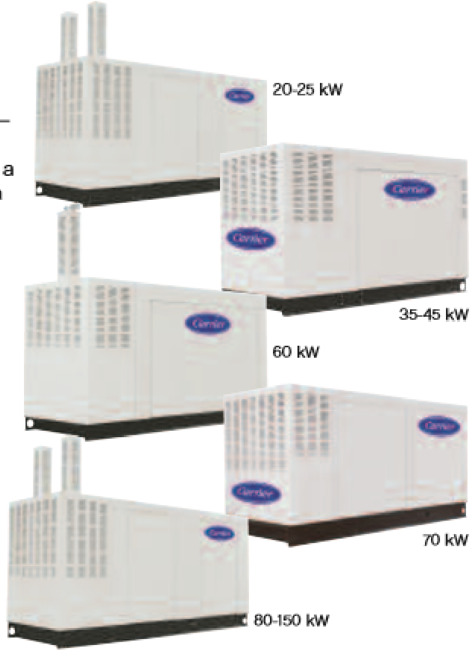
Serie comercial

Para uso comercial / industrial leve

20-150 kW

Energía auxiliar continua para todas las aplicaciones.
La serie comercial de generadores auxiliares Carrier les brinda a restaurantes, gasolineras, oficinas y otros negocios una máxima protección contra apagones por una mínima inversión. Los modelos van desde los 20 a 150 kW de potencia y ofrecen una opción de salidas de voltaje con interruptores de transferencia de mayor amperaje. Los interruptores de transferencia se venden por separado. Vea los interruptores de transferencia necesarios en el siguiente cuadro.

- **Modo ultra silencioso:** la característica de autoverificación con patente en trámite permite que el generador funcione a rpm reducidas, disminuyendo considerablemente la emisión de sonido.
- **Pintura superior:** acabado pintado, texturado y resistente para una duración inigualable.
- **Diseño seguro:** listado por el UL/regulación automática de voltaje y regulador electrónico para artefactos eléctricos sensibles.
- **Combustible continuo:** los modelos funcionan con gas natural o gas propano líquido.



Potencia nominal GPL/GN KW	20	25	35	45	60	70	80	100	100	130	150
Amperios nominales a 60 Hz											
120/240 V 1Ø, 1,0 fp	N/A	N/A	N/A	N/A	250	292	333	417	417	542	625
120/208 V, 3Ø, 0,8 fp	70	87	122	156	208	243	278	347	347	452	521
277/480 V, 3Ø, 0,8 fp	N/A	N/A	53	68	90	105	120	151	151	196	226
RPM del motor/alternador	3600/3600	3600/3600	3600/3600	3600/3600	3600/3600	1800/1800	3600/3600	3600/3600	2300/1800	3000/1800	3600/3600
Motor	1.5L	1.6L	2.4L	2.4L	3.0L	6.8L	4.6L	5.4L	6.8L	6.8L	6.8L
Consumo de combustible											
Propano líquido pies cúbicos/hr	125 (3.44)	183 (5.0)	222.3 (6.1)	286 (7.86)	376.3 (10.34)	411 (11.3)	442 (12.1)	553 (15.2)	507 (13.80)	719 (19.8)	830 (22.8)
Gas natural pies cúbicos/hr	315	442	560	720	960	1020	1100	1374	1260	1786	2061
Dimensiones (LxWxH en pulgadas)*	71x29.5x36	71x29.5x36	77x34x45	77x34x45	89x34x48*	116x37x55	116x37x55*	116x37x55*	116x37x55*	116x37x55*	116x37x55*
Peso del generador (lb) Acero	1020	1025	1393	1414	1650	2185	2010	2311	2705	2873	2666
Aluminio	930	935	1276	1297	1513	2040	1836	2137	2531	2699	2492
Interruptor de transferencia necesario	RTS 100-200	RTS 100-200	RTS 100-200	RTS 100-200	RTS 100-200	HTS 150-400	HTS 150-400	HTS 200-600	HTS 200-600	HTS 200-600	HTS 300-800

La altura no incluye la medida del tubo de escape.

Figure 33: Technical specifications of the generators

ANNEX II: Load profile generator

The LoadProfileGeneration (LPG) is a program that uses behavior Simulation to create load profiles for different types of households. Behavior simulation, as shown in the figure below, takes into account the desires of each type of person in a household and considers different activities to meet those desires. This behavior simulation is based on a psychological model from a German psychologist. In order to know which devices can satisfy these needs or desires, the creator of the platform did a market research, surveys, and study of statistical data.

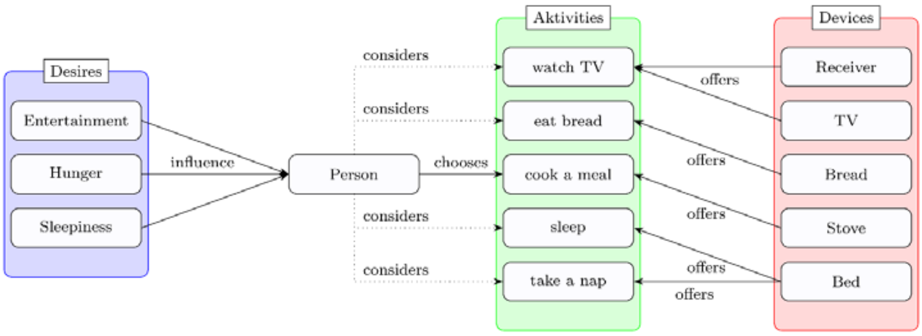
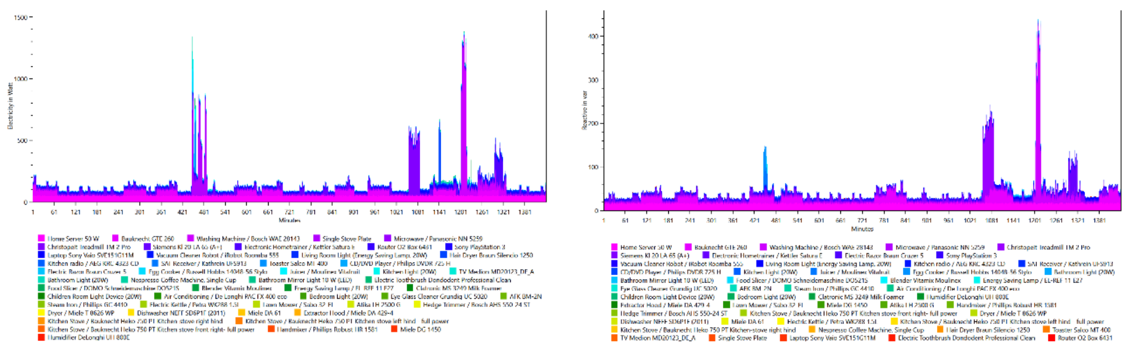


Figure 34: Behaviour simulation [59]

To define the types of users in a household there are two options:

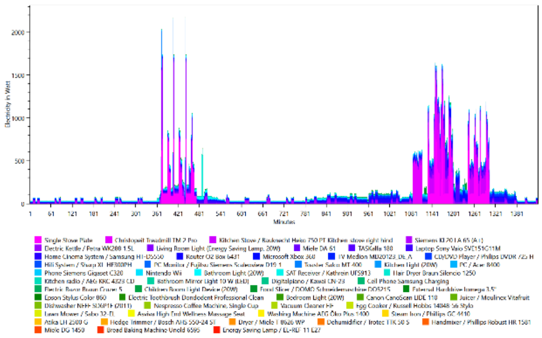
- Choosing predefined households, as it has been done in this project, and validating behavior simulation
- Creating customized households where behavior simulation of the constituents of the household can be also fully customized

In the following figures, an overview of the load profile for every household during an average day. On the left, the active load profile and on the right, the reactive load profile.

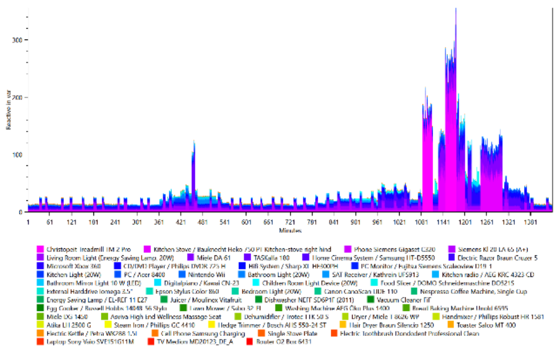


(a) Active Load *(b) Reactive Load*

Figure 35: Consumer load profile, Couple both at work

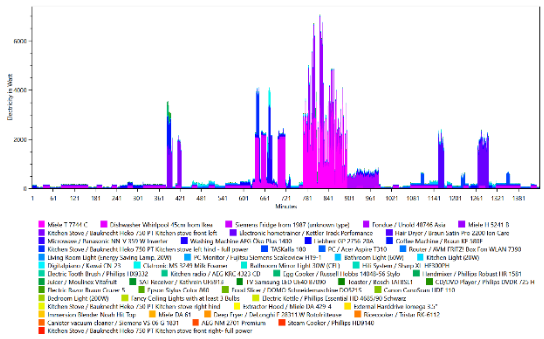


(a) Active Load

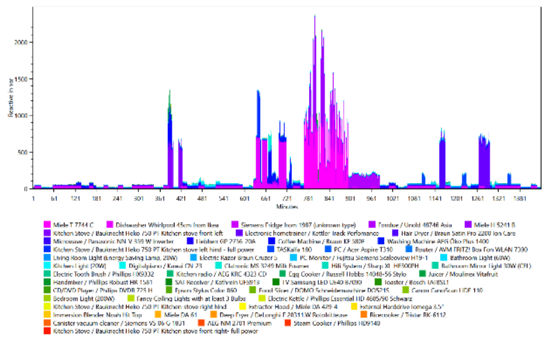


(b) Reactive Load

Figure 36: Consumer load profile, Family, one child, both at work

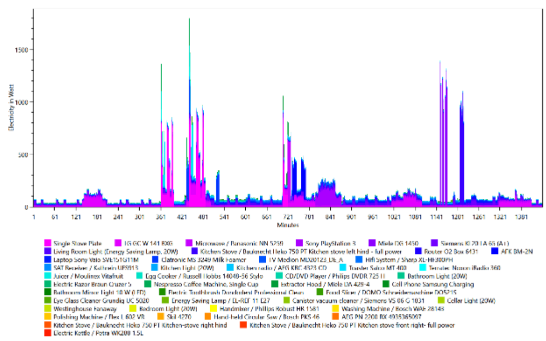


(a) Active Load

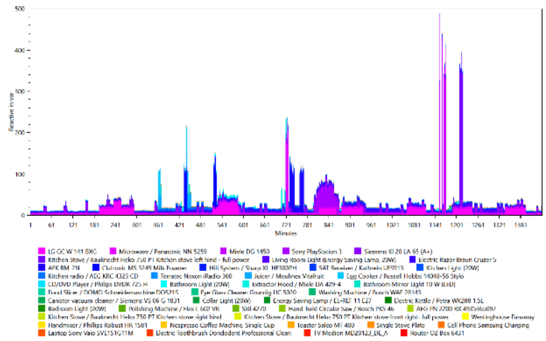


(b) Reactive Load

Figure 37: Consumer load profile, Couple 30-60 both at work with homehelp

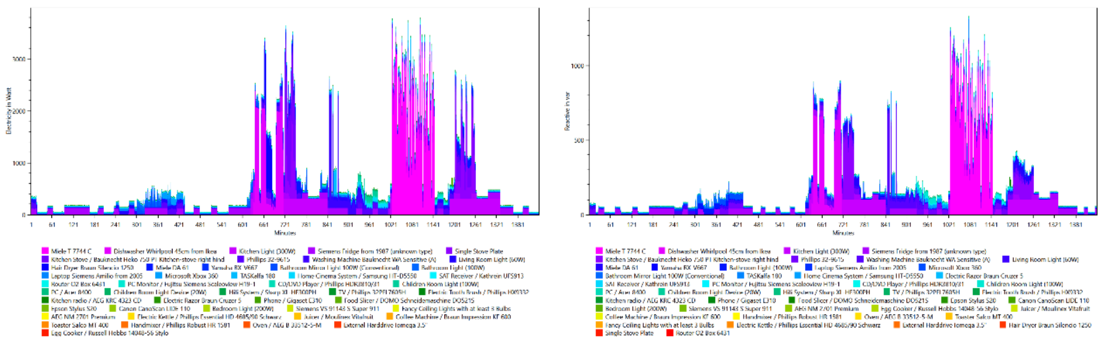


(a) Active Load



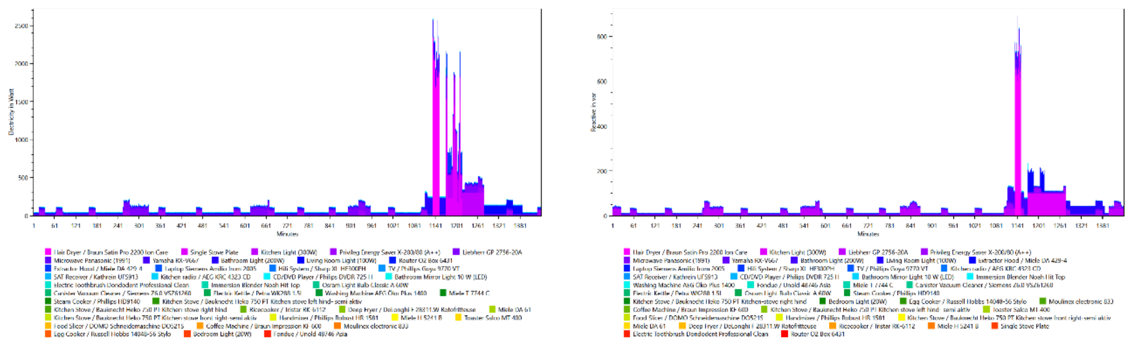
(b) Reactive Load

Figure 38: Consumer load profile, Jak Jobless



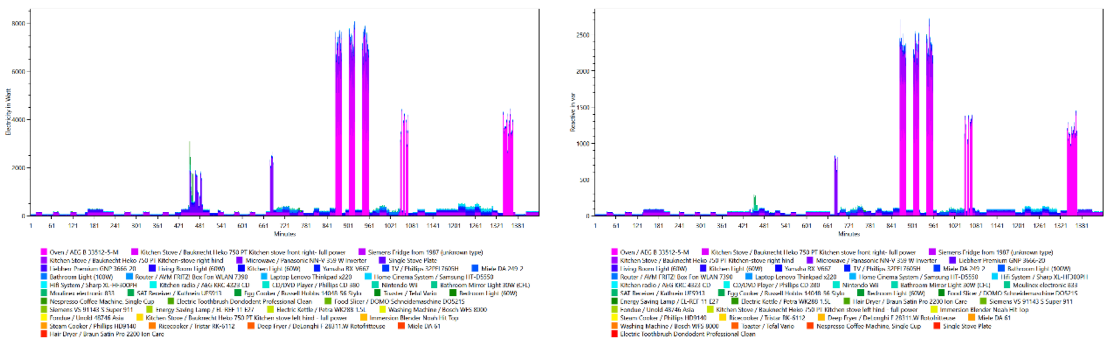
(a) Active Load (b) Reactive Load

Figure 39: Consumer load profile, Family 2 children, parents without work



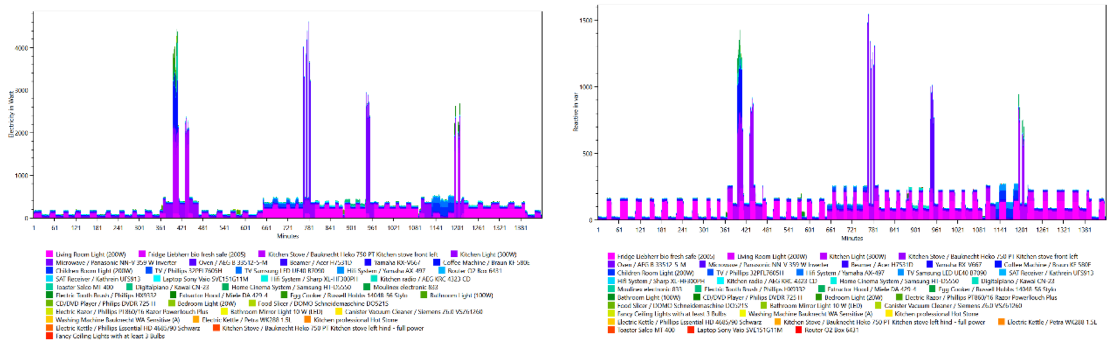
(a) Active Load (b) Reactive Load

Figure 40: Consumer load profile, Single woman under 30 without work



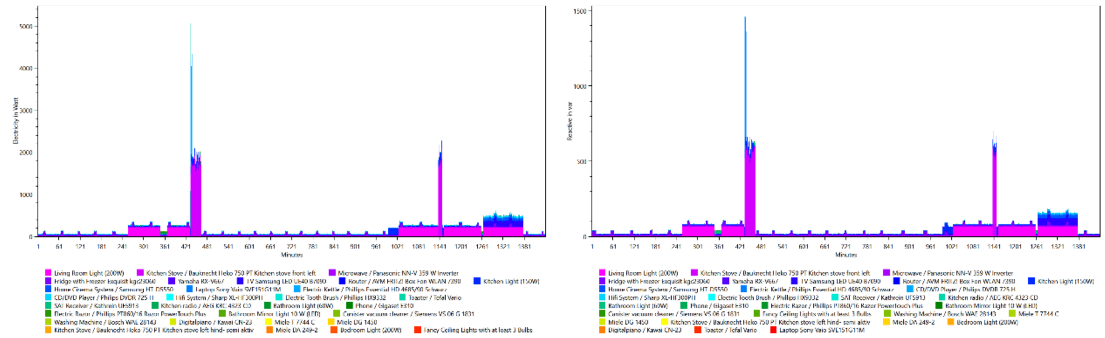
(a) Active Load (b) Reactive Load

Figure 41: Consumer load profile, single woman under 30 without job



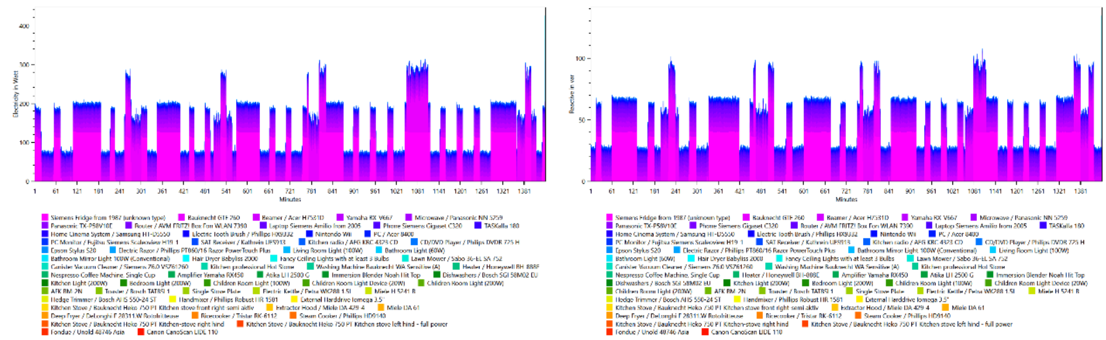
(a) Active Load (b) Reactive Load

Figure 42: Consumer load profile, single man under 30 without job



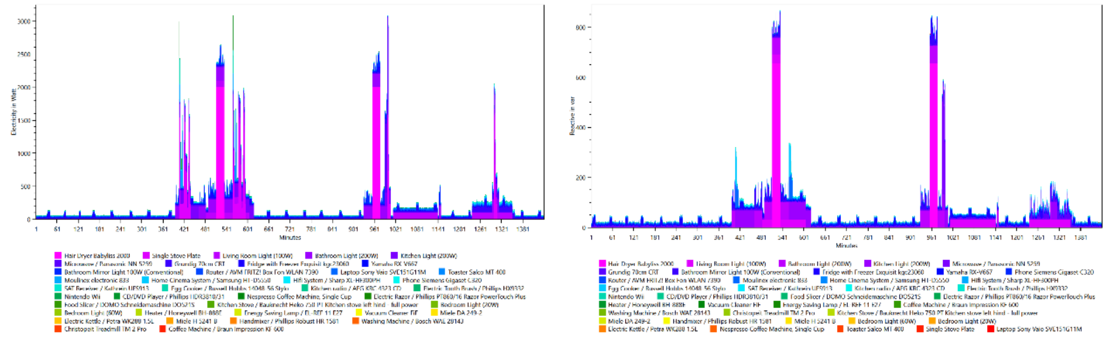
(a) Active Load (b) Reactive Load

Figure 43: Consumer load profile, single man under 30 with job



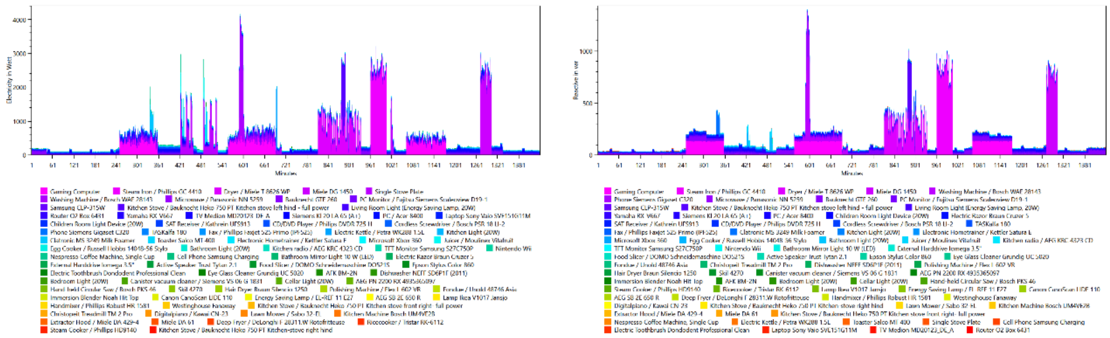
(a) Active Load (b) Reactive Load

Figure 44: Consumer load profile, Family with 2 children, one at home, one at work



(a) Active Load *(b) Reactive Load*

Figure 45: Consumer load profile, student flat sharing



(a) Active Load *(b) Reactive Load*

Figure 46: Consumer load profile, couple with two children, and husband at work

ANNEX III: MATLAB for processing consumption data

LOAD

The load consumption data of the 62 households of the grid is in an Excel file, minute per minute for all year long and the simulation has Timestep of one hour. This code was then created to process data and have it in the right way.

```
clear all
clc
load('TotalLOAD.mat')
% For the 15th March
%d1=74;
%d2=75;

% For the 15th July
d1=197;
d2=198;

% For the 14th December
%d1=349;
%d2=350;
y=0;
m=0;
n=1;
i=1;
h=(d1-1)*60+1;
c=(d2-d1)*24;
X=zeros(c,2);
for i=1:c
    X(i,1)=y;
    y=y+1;
    if y==24
        y=0
    end
    for n=1:60
        m=m+TOTAL(h,2);
        n=n+1;
```

```
        h=h+1;
    end
    X(i,2)=m;
    m=0;
    n=1;
end
%Load hour per hour
P=X(:,2)*1000
load ('Dec_PVOUT.mat') %Change here for different months
load ('Dec_Wind.mat') %Change here for different months
W= VIENTO(:,2)
Irr=PVOUTPUT(:,2)
S=PVOUTPUT(:,3)
save('December.mat', 'P','S','Irr','W') %Change if it's not december
```

PLOT

We will only use this section if we want to visualize the comparison between the load, solar and wind generation.

```
hold on
plot (W)
plot (S)
plot(P)
hold off
title('Wind and Solar Generation vs Load consume')
ylabel('Power [W]')
xlabel('Hours of a day [h]')
legend('Wind Generation','Solar Generation', 'Load')
saveas(gcf,'December.jpeg') %Change file name if it's not december data
% saveas(gcf,'March.jpeg')
% saveas(gcf,'July.jpeg')
```

ANNEX IV: MATLAB for optimization

Optimization problem

The variables of the month to optimize will be imported.

```
clear variables %better efficiency of the code
clc
%Choose the month you need
load ('December.mat')
%load ('March.mat')
%load ('July.mat')
```

Initialize variables

In this part, the following variables will be created:

- timestep (h)
- duration of the simulation (h)
- costs of every source of energy in (€/MWh), then converted to (€/Wh)
- divide costs per each energy (€/Wh)
- maximum capacity of the battery (Wh)

```
nHours= numel(P);
Time=(1:nHours)';
Costs=[35 100 80 300]; %Wind Solar Generators Batteries in €/MWh
Costs=Costs/1000000;
WindCost= Costs(1);
SolarCost= Costs (2);
AuxGenCost= Costs(3)*4; %Applying a fine
BatCost= Costs(4);
Cmax=2205000;
```

Initialization optimization

In this part the optimization, the following parts are initialized:

- the optimization problem (minimizes by default)
- 7 variables to optimize
- the objective function of the optimization

```
powerprob=optimproblem;
pwind=optimvar('pwind',nHours,'Type','continuous','LowerBound', 0,
'UpperBound', W);
m2=optimvar('m2',1,'Type','continuous','LowerBound', 0, 'UpperBound',
1159.5); %must be constant during the whole simulation
pgen=optimvar('pgen', nHours, 'Type', 'continuous','LowerBound', 0,
'UpperBound', 1000000);
psol=Irr*0.1734*m2;
cbati = optimvar('cbati',nHours, 'Type', 'continuous','LowerBound', 0,
'UpperBound', Cmax); %battery capacity before each timestep
```

```
cbatf = optimvar('cbatf',nHours, 'Type', 'continuous','LowerBound', 0,
'UpperBound', Cmax); %battery capacity after each timestep
%variables created to assure that the costs are positive for the
batteries
cbatiabs=optimvar('cbatiabs',nHours, 'Type', 'continuous','LowerBound',
0);
cbatfabs=optimvar('cbatfabs',nHours, 'Type', 'continuous','LowerBound',
0);
%Applying costs to each source
wind=sum(pwind*WindCost);
sol=sum(psol*SolarCost);
gen=sum(pgen*AuxGenCost);
bat=sum((cbatfabs+cbatiabs)*BatCost);
%Objective funcion
powerprob.Objective=wind+sol+gen+bat;
```

Constraints

Initial and final conditions for the battery, having the demand met.

Ci and cf will take different values depending on the month of the simulation.

```
powerprob.Constraints.ci=cbati(1)==0.3*Cmax;
powerprob.Constraints.cf=cbatf(24)==0.3*Cmax; % cbatf assures that
initial charge is the same as final charge
powerprob.Constraints.cap=optimconstr(nHours-1,1);
for i=2:nHours
    powerprob.Constraints.cap(i)=cbatf(i-1)==cbati(i);
end
powerprob.Constraints.batt=optimconstr(nHours,1);
powerprob.Constraints.abs=optimconstr(nHours,1);
for i=1:nHours
    powerprob.Constraints.batt(i)=(cbatf(i)-cbati(i))==(pwind(i)+psol(i)-
P(i));
    powerprob.Constraints.abs(i)=(cbatf(i)-cbati(i))==(cbatfabs(i)-
cbatiabs(i));
end
powerprob.Constraints.isDemandMet=pwind+psol+pgen-(cbatf-cbati)==P;
```

Results

To solve this optimization problem, a lineal programming solver is used.

Then, the solutions are plot.

```
options = optimoptions('linprog');
[solu,TotalCost,exitflag,output] =solve(powerprob, options)
Wind=solu.pwind
Sol=solu.m2*Irr*0.1734;
G=solu.pgen;
Bi=solu.cbati;
Bf=solu.cbatf;
COSTi=solu.cbatiabs;
COSTf=solu.cbatfabs;
figure;
```

```
hold on;
plot(-(Bf-Bi))
plot(Wind)
plot(Sol)
plot(G)
plot(P)
hold off
legend('Battery','Wind Generation','Solar Generation','Auxiliary
Generators','Load')
ylabel('Power [W]')
xlabel('Hours of a day [h]')
%saveas(gcf, 'Optjuly.jpeg')
saveas(gcf,'Optdec.jpeg')
%saveas(gcf, 'Optmarch.jpeg')
save('DecOpt.mat','Wind','Sol','G','P','COSTf','COSTi')
```

ANNEX V: Wind generation data

Average day in March		
Time [h]	Wind [m/s]	Power [W]
0	5	300
1	5	300
2	5	300
3	4	100
4	4	100
5	4	100
6	4	100
7	4	100
8	4	100
9	4	100
10	4	100
11	4	100
12	7	500
13	7	500
14	7	500
15	6	450
16	6	450
17	6	450
18	6	450
19	6	450
20	6	450
21	4	100
22	4	100
23	4	100

Table 29: Average wind generation in March

Average day in July		
Time [h]	Wind [m/s]	Power [W]
0	3	0
1	3	0
2	3	0
3	3	0
4	3	0
5	3	0
6	4	100
7	4	100
8	4	100
9	1	0
10	1	0
11	1	0
12	4	100
13	4	100
14	4	100
15	6	450
16	6	450
17	6	450
18	4	0
19	4	0
20	4	0
21	2	0
22	2	0
23	2	0

Table 30: Average wind generation in July

Average day in December		
Time [h]	Wind [m/s]	Power [W]
0	3	0
1	3	0
2	3	0
3	5	300
4	5	300
5	5	300
6	7	500
7	7	500
8	7	500
9	6	450
10	6	450
11	6	450
12	8	800
13	8	800
14	8	800
15	10	1500
16	10	1500
17	10	1500
18	11	2000
19	11	2000
20	11	2000
21	10	1500
22	10	1500
23	10	1500

Table 31: Average wind generation in December

ANNEX V: Solar generation data

Average day in March		
Time [h]	Irrad [W/m2]	Power [W]
0	0	0
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	88	17693,0424
7	259,5	52174,36935
8	463,5	93190,05855
9	635,75	127822,1785
10	757,75	152351,1691
11	820,25	164917,2503
12	820,25	164917,2503
13	757,75	152351,1691
14	635,75	127822,1785
15	463,5	93190,05855
16	259,5	52174,36935
17	70	14074,011
18	0	0
19	0	0
20	0	0
21	0	0
22	0	0
23	0	0

Table 34: Average solar generation in March

Average day in July		
Time [h]	Irrad [W/m2]	Power [W]
0	0	0
1	0	0
2	0	0
3	0	0
4	0	0
5	47,25	9499,957425
6	151	30359,6523
7	338,5	68057,89605
8	529,75	106510,1047
9	692,75	139282,4446
10	809,5	162755,8844
11	870,25	174970,1153
12	870,25	174970,1153
13	809,5	162755,8844
14	692,75	139282,4446
15	529,75	106510,1047
16	338,5	68057,89605
17	151	30359,6523
18	63	12666,6099
19	0	0
20	0	0
21	0	0
22	0	0
23	0	0

Table 33: Average solar generation in July

Average day in December		
Time [h]	Irrad [W/m2]	Power [W]
0	0	0
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	0	0
7	124	24931,1052
8	254,75	51219,34718
9	416,5	83740,36545
10	528	106158,2544
11	584,75	117568,2562
12	584,75	117568,2562
13	528	106158,2544
14	416,5	83740,36545
15	254,75	51219,34718
16	99	19904,6727
17	0	0
18	0	0
19	0	0
20	0	0
21	0	0
22	0	0
23	0	0

Table 32: Average solar generation in December